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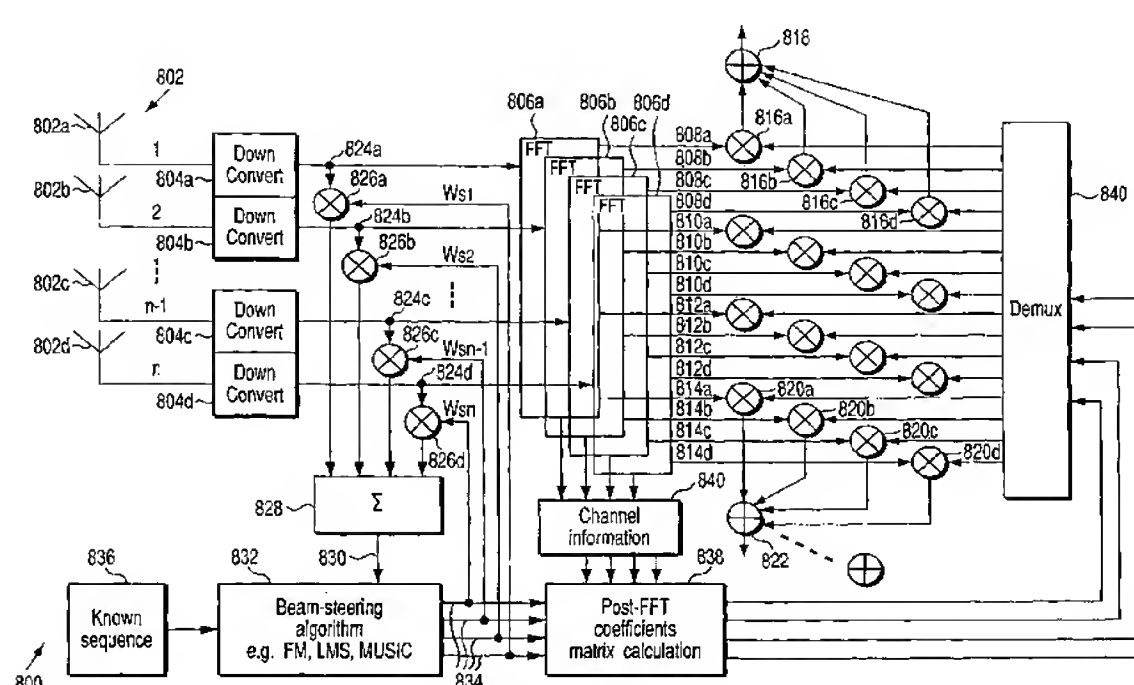
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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: ANTENNA SIGNAL PROCESSING SYSTEMS



(57) Abstract: A B S T R A C T This invention relates to improved antenna techniques particularly for orthogonal frequency division multiplexed (OFDM) communications systems. A signal processing system (800) for determining weights for an adaptive antenna, the antenna having a plurality of antenna elements (802a-d) each for receiving a signal comprising a plurality of subcarriers, the system comprising, a plurality of inputs for receiving signals from the plurality of antenna elements, a time-to-frequency domain transformer (806) for each input for transforming the signal from each input to a plurality of subcarrier signals, a first weight determiner (802) coupled to the inputs, before the time-to-frequency domain transformer in the signal path, and configured to determine a first set of weights, one for each input, and a second weight determiner (838) coupled to the first weight determiner and configured to determine, from the determination of the first set of weights, at least one second set of weights comprising a frequency-domain weight for a subcarrier signal derived from each of the inputs. By calculating a first set of weights in the time-domain and then modifying these for each subcarrier for application in the frequency domain the weight calculation process is simplified and can be performed faster.

## D E S C R I P T I O N

## ANTENNA SIGNAL PROCESSING SYSTEMS

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## Technical Field

This invention relates to improved antenna techniques, particularly for Orthogonal Frequency Division Multiplexed (OFDM) communication systems.

## Background Art

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Orthogonal frequency division multiplexing is a well-known technique for transmitting high bit rate digital data signals. Rather than modulate a single carrier with the high speed data, the data is divided into a number of lower data rate channels each of which is transmitted on a separate subcarrier. In this way the effect of multipath fading is mitigated. In an OFDM signal the separate subcarriers are spaced so that they overlap, as shown for subcarriers 12 in spectrum 10 of FIG. 1A. The subcarrier frequencies are chosen that so that the subcarriers are mutually orthogonal, so that the separate signals modulated onto the subcarriers can be recovered at the receiver. One OFDM symbol is defined by a set of symbols, one modulated onto each subcarrier (and therefore corresponds to a plurality of data bits). The subcarriers are orthogonal if they are spaced apart in frequency by an interval of  $1/T$ , where  $T$  is the OFDM symbol period.

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An OFDM symbol can be obtained by performing an inverse fourier transform, preferably an Inverse Fast Fourier Transform (IFFT), on a set of input symbols. The input symbols can be recovered by performing a  
5 fourier transform, preferably a fast fourier transform (FFT), on the OFDM symbol. The FFT effectively multiplies the OFDM symbol by each subcarrier and integrates over the symbol period  $T$ . It can be seen that for a given subcarrier only one subcarrier from  
10 the OFDM symbol is extracted by this procedure, as the overlap with the other subcarriers of the OFDM symbol will average to zero over the integration period  $T$ .

Often the subcarriers are modulated by QAM (Quadrature Amplitude Modulation) symbols, but other  
15 forms of modulation such as Phase Shift Keying (PSK) or Pulse Amplitude Modulation (PAM) can also be used. To reduce the effects of multipath OFDM symbols are normally extended by a guard period at the start of each symbol.

20 Provided that the relatively delay of two multipath components is smaller than this guard time interval there is no inter-symbol interference (ISI), at least to a first approximation.

FIG. 1B shows an exemplary OFDM transmitter 100  
25 (here in a mobile terminal, MT) and an exemplary OFDM receiver 150 (here in an access point, AP). In the transmitter 100 a source 102 provides data to a

baseband mapping unit 104, which optionally provides forward error correction coding and interleaving, and which outputs modulated symbols such as QAM symbols. The modulated symbols are provided to a multiplexer 108 which combines them with pilot symbols from a pilot symbol generator 106, which provides reference amplitudes and phases for frequency synchronization and coherent detection in the receiver (in other arrangements differential detection may be employed). The combination of blocks 110 converts the serial data stream from multiplexer 108 to a plurality of parallel, reduced data rate streams, performs an IFFT on these data streams to provide an OFDM symbol, and then converts the multiple subcarriers of this OFDM symbol to a single serial data stream. This serial (digital) data stream is then converted to an analogue time-domain signal by digital-to-analogue converter 112, up-converted by up-converter 114, and after filtering and amplification (not shown) output from an antenna 116. Antenna 116 may comprise an omni-directional antenna, a sectorised antenna or an array antenna with beamforming.

The signal from antenna 116 of transmitter 100 is received by an antenna 152 of receiver 150 via a "channel" 118. Typically the signal arrives at antenna 152 as a plurality of multipath components, with a plurality of different amplitudes and phases, which

have propagated via a plurality of different channels or paths. These multipath components combine at the receiver and interfere with one another to provide an overall channel characteristic typically having a number of deep nulls, rather like a comb, which generally change with time (particularly where the transmitter or receiver is moving). Often there will be a number of transmitters in the same general location, for example an office, and this gives rise to co-channel interference, which can be more problematic than multipath.

The antenna 152 of receiver 150 is coupled to a down-converter 154 and to an analogue-to-digital converter 156. Blocks 158 then perform a serial-to-parallel conversion, FFT, and parallel-to-serial re-conversion, providing an output to demultiplexer 160, which separates the pilot symbol signal 162 from the data symbols. The data symbols then demodulated and de-mapped by base-band de-mapping unit 164 to provide a detected data output 166. Broadly speaking the receiver 150 is a mirror image of the transmitter 100. The transmitter and receiver may be combined to form an OFDM transceiver.

OFDM techniques may be employed in a variety of applications and are used, for example, for military communication systems and high definition tv. Here, applications of the invention will be discussed with

particular reference to the HIPERLAN (High Performance Radio Local Area Network) Type 2 standard

([www.etsi.org/technicalactiv/hiperlan2.htm](http://www.etsi.org/technicalactiv/hiperlan2.htm), and

DTS/BRAN-0023003 v 0.k). Although applications of the

5 invention are not limited to this environment HIPERLAN 2 wireless local area network communications are managed by a common node, the access point.

The receiver of FIG. 1B is somewhat simplified as, in practice, there is a need to synchronize the FFT  
10 window to each OFDM symbol in turn, to avoid introducing non-orthogonality and hence Inter-Carrier Interference (ICI). This may be done by auto-correlating an OFDM symbol with the cyclic extension of the symbol in the guard period but it is generally  
15 preferable, particularly for packet data transmission, to use known OFDM (training) symbols which the receiver can accurately identify and locate, for example using a matched filter. It will be appreciated that this matched filter operates in the time domain, that is  
20 before the FFT is carried out (as opposed to the post-FFT frequency domain). In a packet data system data packets may be provided with a preamble including one or more of these training symbols.

FIGS. 2A and 2B show, respectively, a receiver  
25 front end 200 and receiver signal processing blocks 250 of a HIPERLAN 2 mobile terminal (MT) OFDM receiver. The receiver 250 shows some details of the



analogue-to-digital conversion circuitry 252, the synchronization, channel estimation and control circuitry 254 and the de-packetising, de-interleaving and error correcting circuitry 256.

5           The front end 200 comprises a receive antenna 202 coupled to an input amplifier 204 and a mixer 206, which has a second input from an IF oscillator 208 to mix the RF signal to IF. The IF signal is then provided to an automatic Automatic Gain Control (AGC) amplifier 212 via a band pass filter 210, the AGC stage  
10           being controlled by a line 226 from control circuitry 254, to optimize later signal quantisation. The output of AGC 212 provides an input to two mixers 214, 216, which are also provided with quadrature signals from an  
15           oscillator 220 and splitter 218 to generate quadrature I and Q signals 222, 224. These I and Q signals are then over-sampled, filtered and decimated by analogue-to-digital circuitry 254. The over-sampling of the signal aids the digital filtering, after which the  
20           signal is rate reduced to the desired sample rate.

          It is desirable (but not absolutely essential) to compensate for the effects of the transmission channel. This can be done using a known symbol, for example in preamble data or one or more pilot signal. In the  
25           receiver 250 of FIG. 2 a known preamble symbol, referred to as the "C symbol", is used to determine a channel estimate. The receiver synchronizes to the

received signal and switch 258 is operated to pass the received C symbol to channel estimator 260. This estimates the effect of the channel (rotation of the symbols in the sub-carriers) on the known C symbol so that the effects of the channel can be compensated for, by multiplying by the complex conjugate of the channel response. Alternatively the one or more pilot signals (which also contain known symbols) can be used to determine a channel estimate. Again the phase rotation and amplitude change required to transform the received pilot into the expected symbol can be determined and applied to other received symbols. Where more than one pilot is available at more than one frequency improved channel compensation estimates can be obtained by interpolation/extrapolation to other frequencies using the different frequency pilot signals.

In FIGS. 2A and 2B the receiver front end 200 will generally be implemented in hardware whilst the receiver processing section 250 will often be implemented in "software", as illustrated schematically by Flash RAM 262 using, for example, ASICs, FPGAs or one or more DPS (digital signal processor) chips. A similar division between hardware and software will generally be present in the transmitter. However the skilled person will recognize that all the functions of the receiver of FIGS. 2A and 2B (or of an equivalent transmitter) could be performed in hardware. Similarly



the exact point at which the signal is digitized in a software radio will generally depend upon a cost/complexity/power consumption trade-off, as well as upon the availability of suitable high speed analogue/digital converters and processors, and that the RF signal could be digitized at IF or a higher frequency.

FIG. 3 shows an example of a Media Access Control (MAC) frame 300 of a packet data communications system including preamble sequences. The MAC frame includes a broadcast channel (BCH) burst 302, a frame channel (FCH) burst 304, an access feedback channel (ACH) burst 306, a down-link (DL) burst 308, an up-link (UL) burst 310, a direct link (DiL) burst 312, and a random access (RCH) burst 314, all of which contain a preamble sequence.

FIGS. 4A to 4E show, respectively, a broadcast burst, downlink burst, an uplink burst with a short preamble, uplink burst with a long preamble, and a direct link burst of a HIPERLAN 2 physical layer signal. Each of these bursts comprises a preamble portion 400 and a data payload portion 402. The preamble portions 400 comprise one or more of three basic OFDM symbols, denoted A, B and C. The values of these symbols are known and A and B (and, if desired, C) can be recovered in the time domain (pre-FFT). These symbols are generally used to establish the frame

and frequency synchronization and to set the FFT window for the data following the symbols; they may also be employed to control AGC stage 212. In the receiver of FIGS. 2A and 2B are recovered in the time domain and C is recovered in the frequency domain, that is post-FFT.

FIG. 5 illustrates, schematically, the use of these (known) preamble symbols for frame detection 502 based on RSSI (Received Signal Strength Indication), automatic gain control 504, frame synchronization 506, and frequency synchronization 508; a schematic illustration of the preamble portion of an MAC frame 500 is also illustrated for comparison.

FIG. 6 shows a plot 600 in the frequency and time domain illustrating the relative positions of preamble sequences 602, pilot signals 604, and data signals 606 for HIPERLAN 2, which has 48 data sub-carriers and 4 pilots (and one unused, central carrier channel 608). As can be seen from FIG. 6 the first four OFDM symbols comprise preamble data, and the pilot signals 604 continue to carry their preamble symbols. However on the remaining (data-bearing) sub-carriers OFDM symbols 5 onwards carry data. In other OFDM schemes similar plots can be drawn, although the preamble and pilot positions may vary (for example, the pilots need not necessarily comprise continuous signals).

It has previously been mentioned that OFDM is a useful technique for alleviating the effects of

frequency selective fading caused by multipaths.  
However with particularly high data rates or in  
particularly severe multipath environments OFDM  
communications systems can still suffer from the  
5 effects of multipath fading. Moreover in indoor  
wireless environments, such as small office wireless  
LANs, there will often be a number of similar systems  
operating simultaneously in the same frequency band,  
because of limited spectrum availability. This can  
10 result in server co-channel interference.

One technique which has been proposed for  
combating such multipath and co-channel interference is  
the use of a sectorised transmit and/or receive  
antenna. The region to be covered is divided into a  
15 number of sectors, typically 3, 4 or 6, and one antenna  
(or more where diversity is employed) is provided for  
each sector, the patterns of the antennas being  
arranged to each cover mainly just one sector. In  
effect the main beam of each of the sector antennas  
20 points in a different direction and by selecting the  
transmit and/or receive direction the effects of  
multipath components and/or co-channel interference  
arriving from unwanted directions can be reduced.  
HIPERLAN 2, for example, supports the use of up to  
25 seven sectors at the Access Point. Some of the  
benefits of employing a sectorised switching array  
antenna in a HIPERLAN 2 environment are described in

"Performance of HIPERLAN 2 using Sectorised Antennas"

A. Dufexi, S. Armour, A. Nix, P. Karlsson and D. Bull,  
IEE Electronics Letters 15th February 2001, volume 37  
no. 4, page 245.

5           Another approach employed to mitigate the effects  
of multipath and co-channel interference uses a  
beamforming antenna array, such as a linear array of  
antenna elements in which the inter-antenna spacing is  
approximately one half a (carrier) wavelength. Signals  
10 from the antennas are combined, with appropriate phase  
and amplitude weightings, to provide a combined  
response with one or more lobes or beams. An array  
comprising  $n$  elements can be arranged to provide up to  
 $n-1$  beams.

15           There are a number of different beamforming  
algorithms which may be applied to such an adaptive  
antenna array and details of these will be well known  
to the skilled person. One commonly used algorithm is  
the Constant Modulus Algorithm (CMA), described in J.R.  
20 Treichler and B.G. Agee, "A New Approach to Multipath  
Correction of Constant Modulus Signals", IEEE Trans.  
Acoust. Speech and Signal Process., vo. ASSP-31, no. 2,  
page 459, 1983, which is hereby incorporated by  
reference. Broadly speaking this algorithm iteratively  
25 determines the weights for combining the signals from  
the antenna elements based upon a cost function chosen  
to make the spectrum of the combined signals

approximately flat. The phase angles of the weights are chosen so that the beams point in the direction of maximum signal power, or, alternatively, so that nulls are formed in the directions of the unwanted multipath components or co-channel interference.

Determining appropriate weights for the antenna array elements is relatively straightforward in a narrow band system but in an OFDM receiver, where the band width occupied by the group of sub-carriers is normally  $> 1$  MHz and in many cases  $> 10$  MHz, a single set of weights is unlikely to be optimal across the entire bandwidth and may only be valid, for example, at the center of the frequency band. This can be understood, for example, from the consideration that the antenna element spacing, in terms of fractions of a sub-carrier wavelength, varies across the OFDM frequency band. In the receiver of FIG. 1 adaptive array weights may be applied at points 168, 170, or 172 but applying the array weights at positions 168 or 170 (pre-FFT) will not normally result in a good set of estimated weights across the frequency band.

One solution to this problem is therefore to apply weightings after the FFT, at point 172, where different sets of weights can be applied to each sub-carrier. FIG. 7 shows an OFDM receiver 700 in which a separate set of weights is applied to each sub-carrier in this way. However it will be appreciated that with  $K$

sub-carriers and L antenna elements a total  $K \times L$  weights must be determined, which is a lengthy and processor-intensive task adding considerably to the receiver complexity. EP 0852407 describes an arrangement in which an operational band is partitioned into four equal sub-bands, one set of weights being calculated for each sub-band rather than for each sub-carrier, to reduce the number of weights to be calculated. However this is still a relatively complicated procedure and, moreover, produces a sub-optimal result. An alternative approach is described in Fujimot et al, "A Novel Adaptive Array Utilizing Frequency Characteristics", IEICE Trans. Commun., vol., E 83-B, no. 2 February 2000, page 371, which is hereby incorporated by reference, in which the post-FFT separated sub-carriers are used to determine a single set of pre-FFT time domain weights using CMA. This approach provides a considerable simplification of the weight determining procedure but, again, the weights are sub-optimal.

US 6,249,250 describes OFDM adaptive antenna weight determination techniques for use in either the time or frequency domain (but not both simultaneously). Other weight-determination techniques involving sub-carrier clustering are described in Japanese patent application number 2000-391221 filed on 22nd December 2000, inventor Hidehiro Matsuoka, and British patent



application number 0108026.6 filed on 30th March 2001  
entitled "Adaptive Antenna".

The above-described weight calculation techniques  
for array antennas each have pros and cons, some  
5 providing relatively accurate weight determination at  
the expense of complex and time-consuming processing,  
others having simpler, faster weight determination  
algorithms but in general providing poorer weight  
estimates. There is therefore a need for improved  
10 array antennas and weight determination techniques  
which can provide good weight estimates without  
imposing an excessive signal processing burden.

#### Disclosure of Invention

According to the present invention there is  
15 therefore provided a signal processing system for  
determining weights for an adaptive antenna, the  
antenna having a plurality of antenna elements each for  
receiving a signal comprising a plurality of  
subcarriers, the system comprising, a plurality of  
20 inputs for receiving signals from the plurality of  
antenna elements, a time-to-frequency domain  
transformer for each input for transforming the signal  
from each input to a plurality of subcarrier signals, a  
first weight determiner coupled to the inputs, before  
25 the time-to-frequency domain transformer in the signal  
path, and configured to determine a first set of  
weights, one for each input, and a second weight

determiner coupled to the first weight determiner and configured to determine, from the determination of the first set of weights, at least one second set of weights comprising a frequency-domain weight for a subcarrier signal derived from each of the inputs.

The signal processing system greatly simplifies the calculation of weights for each subcarrier (or for a subcarrier group) in the frequency domain as compared with prior art techniques. This in turn allows the power consumption and/or cost of providing an adaptive antenna with digital beamforming in the frequency domain to be significantly reduced. The system is also flexible enough to allow additional adaptive signal processing methods to be applied in the frequency domain to further improved system performance where necessary.

In one embodiment the time domain or pre-FFT processing to determine the first set of weights has the effect of defining a direction, for example a direction with the highest signal-to-interference ratio for the band. One or more directions may alternatively be determined by identifying those directions which are above a threshold of received power level. This direction or directions, or more generally a spatial property or beam pattern defined by the first set of weights, is preferably substantially maintained when calculating the second set of weights. The algorithm

used to determine the second set or sets of weights  
aims to maintain the beam direction or pattern and, in  
a simple embodiment, comprises a small number of  
multiply operations, for example one for each array  
5 antenna element. Thus the second sets of weights are  
chosen so that the antenna beam for each subcarrier has  
the same direction as that determined when calculating  
the first set of weights. The values of the sets of  
weights will be different because the subcarriers are  
10 at different frequencies.

The first weight determiner effectively functions  
as a direction of arrival (DoA) detector, the output of  
which is used by the second weight determiner. Thus in  
the invention the function of the first weight  
15 determiner may be performed by any form of direction of  
arrival detector.

Various measures may be used to determine the  
initial beam direction (or directions), such as a  
simple measure of received power, but preferably the  
20 system uses the first weight determiner to determine a  
direction (or directions) based upon signal-to-  
interference ratio. This helps discriminate against  
co-channel interference, which can have a relatively  
large received power level. The first weight  
25 determiner may determine a set of weights which aims to  
null out multipath and/or co-channel interference, that  
is an antenna response pattern best characterized as

having one or more nulls rather than one or more main lobes. However this embodiment is less preferable as, particularly in a wide-band system, there may be a large number of multipath components to attenuate  
5 whereas generally speaking, only one or a few lobes will serve to pick out the signals with the best signal-to-interference ratios. The first set of weights may be determined conventionally by minimizing a cost function which increases as the signal-to-  
10 interference ratio goes down.

The signal processing system may be applied at an Access Point or base station or at the mobile end, for example in a Mobile Terminal. The system may be implemented in hardware, for example in silicon, or in  
15 software, or in a combination of the two. Preferably the subcarriers are substantially mutually orthogonal, although the system may also be employed where the subcarriers do not overlap and thus do not need to be orthogonal. However, the system is particularly suited  
20 to processing OFDM (Orthogonal Frequency Division Multiplexed) signals.

The second weight determiner preferably calculates the second sets of weights from the first set of weights, but in embodiments it may instead use the  
25 results from an intermediate calculation, and in this case it may not be necessary to complete the calculation to determine a usable first set of weights.

One second set of weights is preferably provided for each subcarrier signal (a set of weights comprising a weight for each version of a subcarrier, one version derived from the signal from each of the antenna elements) but, where a still further simplified calculation is required, groups of subcarriers may share sets of weights. Thus the subcarriers may be arranged in a number of groups each of which has one of the second sets of weights. Each of the weights in a second set of weights will generally, however, have been derived from the received signals from all the array antenna elements. Preferably the second sets of weights are modified by a channel estimate determined from the signal from each of the antenna elements.

15           In embodiments all the signals for each subcarrier are combined after weighting by one of the weights from the second sets of weights. Thus, for example, weighted versions of the first carrier derived from each of the antenna elements are combined to provide a combined first subcarrier output, and the remaining subcarriers are likewise combined. Where one or a group of subcarriers has a quality which is significantly inferior to that of the other subcarriers, for example a significantly worse signal-to-interference ratio, a post-FFT narrowband-type beamforming algorithm may be used separately on the one (or the group of) subcarriers. Techniques for this are

further described in the related case, "Adaptive Antenna", British patent application number 0108026.6, filed by the present applicant on 30th March 2001, the contents of which are hereby incorporated by reference.

5            Preferably the first weight determiner implements a direction of arrival detection algorithm which controls a directional response of the antenna, such as a digital beamforming or beamsteering algorithm. In embodiments where the antenna elements are directional  
10           direction of arrival detection may simply comprise selection of one of the elements based upon a power or signal-to-interference ratio threshold.

          A preferred embodiment of the invention incorporates a signal and interference detector, which  
15           may provide separate signal and interference outputs or a combined output comprising, for example, a signal-to-interference ratio. Preferably the signal and interference detector operates in the time domain, that is before the received signal has been transformed from  
20           the time domain to a frequency domain, typically by a fourier transform for an OFDM signal. One signal and interference detector may be provided for each antenna element or a single signal and interference detector may be shared between the elements, for example on a  
25           time-multiplexed basis.

          Preferably the signal and interference detector determines the strength of the wanted signal and



unwanted interference using a correlation technique. A known portion of the received signal may be correlated with a reference signal to determine the wanted signal strength, and with a signal orthogonal to the reference signal to determine the interference strength. The known portion of the received signal may comprise, for example, a preamble sequence such as a pseudo-noise sequence. The correlation is performed in the time-domain - that is the correlation is between two OFDM symbols and hence an inverse fourier transform is performed on the known (preamble or pseudo-noise) data prior to the correlation. Preferably, therefore, the antenna element selector includes a signal generator to generate the reference signal and signal orthogonal to the reference signal, although this is not essential as an appropriate reference may be extracted from the received data.

The signal processing system may incorporate means for angular diversity reception, combining signals with a high signal-to-interference ratio received from different directions. Thus a plurality of post-FFT second sets of weights may be determined for each sub-carrier and for each beam direction and then the corresponding sub-carriers received from each direction may be combined using diversity reception techniques. As previously described the post-FFT subcarrier weights may be derived from the pre-FFT weight determination

used for defining the beam directions.

In some cases it may be preferable to divide the incoming OFDM signal into a plurality of sub-bands, each sub-band preferably including a number of subcarriers. Separate pre-FFT weight calculations may then be made for each sub-band, which allows an improved accuracy in post-FFT weight determination, particularly where the receiver response is not flat across the bandwidth of interest. Thus preferably a number of subcarriers are allocated to each of the sub-bands and the post-FFT weights for the sub-carriers within a sub-band use the pre-FFT weights determined for that sub-band. The signal processing system may include means for sub-dividing the OFDM signal bandwidth into sub-bands, for example based upon the OFDM pilot signals.

In a related aspect the invention provides a method of determining weights for an adaptive antenna, the antenna having a plurality of antenna elements each for receiving a signal comprising a plurality of subcarriers, the method comprising, receiving a plurality of signals from the plurality of antenna elements, transforming each of the plurality of received signals into a plurality of subcarrier signals, determining a first set of weights, one for each received signal, and determining, using the determination of the first set of weights, at least one

second set of weights comprising a frequency-domain weight for a subcarrier signal derived from each of the received signal inputs signals.

5       The invention also provides a method of adaptive beamforming for an OFDM antenna comprising a plurality of antenna elements, the method comprising, applying a first beamforming algorithm in the time domain to determine at least one antenna beam direction, and calculating a set of weights for application in the  
10       frequency domain to versions of at least one subcarrier, each version of the subcarrier being received by a corresponding one of the antenna elements, the set of weights being calculated using the at least one antenna beam direction.

15       The invention further provides a method of calculating weights for an array antenna for receiving an orthogonal frequency division multiplexed (OFDM) signal comprising a plurality of subcarriers, the method comprising, determining, in a time domain, a  
20       direction of arrival of the OFDM signal at the array antenna, calculating at least one set of weights for application to the subcarriers of the OFDM signal in a frequency domain using the direction of arrival.

25       Here "time domain" is used to refer to a part of the signal path preceding a time-to-frequency or fourier transform and "frequency domain" is used to refer to a part of the signal path following a

time-to-frequency or fourier transform of the received OFDM signal.

In a related aspect the invention provides a carrier carrying processor control code to implement the above-described signal processing systems and method. This processor control code may comprise computer programme code, for example to control a digital signal processor, or other code such as a plurality of register values to set up a general purpose integrated circuit to implement the selector or method. The carrier may comprise a data carrier or storage medium such as a hard or floppy disk, CD- or DVD-ROM, or a programmed memory such as a read-only memory, or an optical or electrical signal carrier. As the skilled person will appreciate the control code may be also be distributed between a plurality of coupled components, for example on a network. The skilled person will further recognize that the invention may be implemented by a combination of dedicated hardware and functions implemented in software.

These and other aspects of the invention will now be further described, by way of example only, with reference to the accompanying figures in which:

#### Brief Description of Drawings

FIGS. 1A and 1B show, respectively, an OFDM symbol and an exemplary OFDM transmitter;

FIGS. 2A and 2B show, respectively, a receiver

front end, and signal processing blocks of a HIPERLAN 2 OFDM receiver;

FIG. 3 shows an exemplary Media Access Control frame of a packet data communications system;

5        FIGS. 4A to 4E show, respectively, a broadcast burst, a downlink burst, an uplink burst with a short preamble, an uplink burst with a long preamble, and a direct link burst of a HIPERLAN 2 physical layer signal;

10        FIG. 5 shows, schematically, uses of the preamble portion of a HIPERLAN 2 broadcast burst in a mobile terminal OFDM receiver;

FIG. 6 shows a frequency-time plot of a HIPERLAN 2 OFDM signal including preamble and pilot signals;

15        FIG. 7 shows an OFDM receiver in which a separate set of weights is applied to each sub-carrier in the frequency domain;

FIG. 8 shows a schematic diagram of an antenna signal processing system according to an embodiment of  
20        the present invention;

FIGS. 9A and 9B show, respectively, a schematic diagram of a signal and interference detector, and a schematic diagram of a signal generator for the signal and interference detector of FIG. 9A;

25        FIG. 10 shows an architecture of an OFDM receiver with pre-FFT digital beam-forming and post-FFT diversity; and

FIGS. 11A and 11B show an OFDM receiver for beam direction diversity reception according to an embodiment of the present invention.

#### Best Mode of Carrying Out the Invention

5 Referring now to FIG. 8, this shows a schematic diagram of an antenna processing system 800 for calculating weights for an adaptive antenna of an OFDM receiver.

10 An array antenna 802 comprises  $n$  directional antenna elements of which four 802a, b, c, d are shown. To each of the respective antenna elements is coupled a downconverter 804a-d and these downconverters in turn provide received signal inputs for a set of fast  
15 fourier transform (FFT) blocks 806a-d. Thus up to this point in the signal processing architecture there is, in effect, a conventional OFDM receiver front end for each antenna element 802. Each FFT block 806 provides a plurality of frequency-domain outputs, one for each  
20 subcarrier. For simplicity, in FIG. 8 outputs for only four such subcarriers are shown but, in practice, there are typically more than ten such subcarriers often more than one hundred subcarriers and sometimes more than one thousand subcarriers.

In FIG. 8 lines 808a-d carry frequency domain  
25 signals for versions of a first subcarrier derived from received signals from antenna elements 802a-d respectively. Similarly lines 810a-b carry versions of



a second subcarrier from respective antenna elements 802a-d, lines 812a-d carry third subcarrier signals from these antenna elements and lines 814a-d carry versions of a fourth subcarrier, one from the signal from each of the antenna elements 802a-d. Each set of each subcarrier has an associated set of multipliers for weighting the subcarrier versions prior to their combination. In the case of the first subcarrier, multipliers 816a-d are provided to multiply the version of the first subcarrier from each antenna element by an appropriate weight prior to summation of these weighted versions of the first subcarrier in summer 818. Likewise multipliers 820a-d are provided for applying weights to the fourth subcarrier on lines 814a-d, the weighted versions of the fourth subcarrier being combined by summer 822. One set of multipliers and one corresponding summer is provided for each set of versions of each subcarrier of the OFDM signal but, for simplicity, only the summers for the first and fourth subcarriers are shown in FIG. 8.

The weights multiplying each version of a subcarrier are generally complex numbers, comprising an amplitude and a phase. The values of the weights are selected to provide an antenna response with one or more beams or lobes pointing towards the direction (or directions) having the greatest received signal power or, preferably, the greatest signal-to-interference

ratio.

For an ideal narrow band system with only one signal path and one interference path it is straightforward for an adaptive array antenna processing system to maximize the desired signal by nulling the interference in the spatial domain, employing a single set of weights. However where the relevant frequency band is relatively wide the application of only a single set of coefficients across the whole band results in a spatial response for the antenna which varies across the frequency band. A conventional way to deal with this problem is to treat each subcarrier in an OFDM system individually, as a narrow-band signal, and calculate the weights for multipliers 816 and 820 accordingly. However this approach is complex and processor-intensive.

The applicants have recognized that, in theory, the subcarrier (or subband) weights should be chosen to reproduce the spatial characteristics of the antenna at the frequency of each subcarrier to mitigate the interference. When looked at in this way it can be recognized the calculation of a separate set of weights for each subcarrier or group of subcarriers (ie. subband) ab initio is unnecessary as the use of spatial information is repeated, that is, the spatial characterization at each subcarrier frequency should, ideally, be the same. Thus the signal processing

system can be simplified if the weights are calculated in stages, a first stage in which the required spatial response of the antenna is determined, and a second stage in which sets of weights for the versions of each subcarrier (or group of subcarriers) are determined making use of the desired spatial response.

In the arrangement of FIG. 8, as will be described further below, a time-domain process is used to determine an approximate spatial response required for the adaptive antenna, and the set of weights determined by this process is then modified to provide a set of weights appropriate to each subcarrier. This significantly reduces the redundancy present in prior art weight calculation processes.

Referring again to FIG. 8, the signals input to FFT blocks 806a-d are tapped at points 824a-d to provide inputs to a further set of multipliers 826a-d. The outputs from the multipliers are combined by summer 828 and provide an input 830 to a conventional beamsteering algorithm 832. The beamsteering algorithm provides a set of outputs 834 comprising weights for input to multipliers 826a-d, one for each antenna element 802a-d. In this way a conventional beamsteering algorithm is applied to the wideband, time-domain OFDM signals from each antenna elements, prior to the FFT operation.

The time-domain adaptive antenna process aims to

spatially separate the desired signal from any interference by controlling the antenna beam pattern. The signal direction of arrival (DoA) information can be determined by employing the same, conventional algorithms and procedures as are used for DoA determination in narrow-band systems. Such methods include the Fourier Method (FM), Least Means Squares (LMS) method, Multiple Signal Classification (MUSIC) method, and the ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques) method.

The purpose of algorithm 832 is to detect the direction of arrival of one signal or of a group of signals, in the presence of multipath, and to spatially separate the signal from the interference. The assumption is made that the spatial characterization of the signal and interference is approximately constant across the applicable frequency band. Making this assumption a matrix of weights or co-efficient for each subcarrier (or for a group of subcarriers) can be calculated in a frequency domain to substantially maintain the spatial characteristics of the antenna.

In a preferred embodiment the antenna beamsteering is based upon a determined signal-to-interference ratio rather than an absolute level of received power. Such a signal-to-interference ratio may be calculated by making use of a known transmitted data sequence such as a preamble portion of an OFDM signal, correlating the

known and received signals as explained in more detail below. For this reason the signal processing system preferably includes a signal generator 836 to provide a version of the known sequence, as transmitted. The  
5 beamsteering algorithm may be chosen to maximize the signal-to-interference ratio (or, alternatively, to minimize the interference-to-signal ratio), as described, for example, in M Fujimoto, N Kikuma and N Inagaki, "Performance of CMA adaptive array optimized  
10 by Marquardt method for suppressing multipath waves", IEICE Trans., vol. J74-B-II, no. 11, 1991, page 599 which is hereby incorporated by reference. Since a measurement of signal-to-interference ratio based upon a preamble at the start of an OFDM data frame is not a  
15 continuous measurement, the assumption is made that the channels for the desired signal and interference (that is amplitude and phase) are quasi-static.

Referring now to FIG. 9A, this illustrates an exemplary signal and interference detector 900 for the  
20 signal processing system of FIG. 8. The input signal on line 903 is provided to first and second cross-correlators 901, 902, the outputs of which are provided to a signal strength detector 904 and to an  
interference strength detector 906 respectively to  
25 provide signal 908 and interference 910 strength outputs for calculating a signal-to-interference strength ratio. Cross-correlator 901 cross-correlates

the input signal with a known reference signal comprising a time-domain OFDM signal generated, for example, from a packet data frame preamble sequence. Cross-correlator 902 cross-correlates the input signal with a signal which is at least partially orthogonal to the known reference signal, and thus extracts an interference component from the input signal, as will be explained in more detail below. Where the reference signal is derived from a preamble data sequence the output of the signal and interference strength detector 900 will only be valid when the preamble sequence is present. In this case the cross-correlators 901, 902 may be arranged to operate over a time window during which the preamble sequence is present. The time window may be determined, for example, by a synchronization process such as an FFT window control process (not shown in FIG. 8). Alternatively one or more pilot signals transmitting a known data sequence substantially continuously may be extracted from the received signal and used in the cross correlation process.

FIG. 9B shows an exemplary signal generator 920 for providing the reference and orthogonal reference signals 912, 914. The signal generator 920 comprises, in the illustrated example, a preamble sequence generator 922, to generate a preamble sequence 924 and a signal 926 orthogonal to the preamble sequence.



These two signals are then inverse fast fourier transformed by IFFT 928 to provide reference signals 912 and 914. In a HIPERLAN 2 system the preamble sequence p may be generated using the polynomial  $s(x) = x^7 + x^4 + 1$  with an initial all ones state, replacing all "1"s with -1 and all "0"s with the number 1.

The operation of the signal and interference detector may be understood by considering a signal (R+I) where R is a known reference symbol and I is an interference contribution. The correlation of (R+I) with R is  $R^2$ , that is the result is a measure of the desired signal strength, assuming that the cross-correlation between the reference signal and the interference is low. The cross-correlation of between (R+I) and  $R^*$ , where  $R^*$  is a signal orthogonal to R, is equal to the cross-correlation of  $R^*$  with I as the cross-correlation of  $R^*$  with R is by definition zero. The cross-correlation of  $R^*$  with I is a measure of the interference strength. Thus the outputs from the signal and interference strength detector 900 can be used to calculate a form of signal-to-interference ratio, which can then be used by the beamsteering algorithm 832 to direct one or more antenna beams towards received signals with the least interference to the desired signal.

The correlation of two orthogonal sequences may be referred to as a zero-value-correlation, in

mathematical terms,

$$\sum_{i=1}^N a_i * b_i = 0; \quad (\text{Equation 1})$$

where,  $a_i$  is the first correlation sequence and  $b_i$  is  
 5 the second correlation sequence (both of length  $N$ ).  
 When the second correlation sequence is correlated with  
 noise or co-channel or multipath interference the  
 result is non-zero. The sequence  $a_i$  is inserted into  
 the data frame, for example, in the preamble. One way  
 10 to format a zero-value-correlated sequence is from a  
 pair of highly correlated sequences. A highly  
 correlated sequence has the property:

$$R_{xx}(n) = \begin{cases} 1, & n = 0 \\ 0, & n = \pm 1, \pm 2, \pm 3, \pm 4, \dots \end{cases} \quad (\text{Equation 2})$$

15 By combining a pair of this kind, zero-value-  
 correlation sequences can be defined. Total received  
 signal energy can be found by calculating the received  
 power, and one measure of the level of unwanted  
 interference energy is indicated by the peak level of  
 20 the zero-value-correlated signal.

The signal and interference detection operation  
 may be carried out at the beginning of data reception  
 and/or every successive packet, or frame-by-frame. The  
 beamforming approach allows the formation of flexible  
 25 beam patterns and, where signals from three or more  
 elements are combined, multiple directional lobes.  
 Suitable beamforming methods are described in more

detail in J.E. Hudson, "Adaptive Array Principles",  
Peter Peregrinus Limited, 1981, which is hereby  
incorporated by reference.

Referring again to FIG. 8, the weights on line 834  
5 from beamsteering algorithm 832 are provided to a  
frequency domain (i.e. post-FFT) weight calculation  
procedure 838. Also input to procedure 838 is channel  
information from a channel information calculation  
block 840. Channel information block 840 has inputs  
10 from FFT procedures 806a-d and provides an amplitude  
and phase value for each subcarrier. As the skilled  
person will be aware, a number of conventional channel  
estimation techniques exist for OFDM based upon, for  
example, the use of a preamble comprising one or more  
15 known OFDM training symbols and/or pilot subcarriers.

The weight for co-efficient calculation procedure  
838 determines weights to be applied to each version of  
each subcarrier, in FIG. 8 by means of exemplary  
multipliers 816a-d and 820a-d. However there is no  
20 need to apply an iterative process such as algorithm  
832 again as since the frequency domain weight are  
chosen to reproduce the same physical direction (or  
directions) as determined in the time domain a simple  
matrix multiplication will suffice. Thus with, for  
25 example, an array antenna with eight elements only  
eight multiplies are required.

The pre-FFT direction of arrival (DoA) calculation

determines a set of weights on the assumption that the distance between each array antenna element is approximately half a wavelength. This assumption is correct at one frequency, typically the center frequency, but to either side of this frequency the element spacing is no longer half a wavelength. Thus the weights may be adjusted by recalculation based upon an antenna array element spacing (in wavelengths) at the wavelength for which the set of weights is required. In one embodiment this calculation is performed by procedure 838. The skilled person will understand that the determination of a set of weights for each subcarrier does not need to make use of any one specific matrix equation.

Sets of weights for each subcarrier are extracted by demultiplexer 840 and provide (complex) inputs to, in FIG. 8, multipliers 816a-d and 820a-d. It will be appreciated that the functional elements of FIG. 8 may be implemented either in hardware or in software. Generally the downconverters 804 will be implemented in hardware, following which the received signals are digitized by analogue-to-digital converters (not shown), the remainder of the signal processing preferably taking place in the digital domain. Thus the functions of elements 806-840 will generally be implemented by software running on a digital signal processing integrated circuit, often a DSP tailored to radio

applications.

The above-described method for extrapolating from pre-FFT weights to post-FFT weights assumes an approximately linear receiver response across the wideband OFDM signal. However in practice this assumption is not necessarily completely true as the frequency response of amplifiers and other signal processing elements in the receive chain is typically not completely flat. For example an amplifier may provide 10 dB of gain at 5 GHz but only 7 dB gain at 4.5 GHz and 5.5 GHz. It is therefore preferable to provide means for compensating for such gain and other variations in response across the wideband channel. This can be done by dividing the wideband OFDM channel into a plurality of sub-bands and determining, in the pre-FFT domain, a set of weights for each sub-band, based upon direction of arrival techniques as previously described. Each of these sets of weights can then be used to derive weights for use in the post-FFT domain, by allocating each subcarrier to one of the sub-bands. It will be appreciated that each of these sub-bands will generally comprise a plurality of subcarriers, for example 100 subcarriers, so that, in effect, the wideband OFDM signal is being sub-divided and the above-described technique applied with each sub-band. Thus, for example, the wideband OFDM signal may be sub-divided into between 4 and 10 sub-bands so

that different sets of pre-FFT weights can be calculated for each of these sub-bands. In this way the burden of post-FFT weight calculation is still significantly reduced since each sub-band will typically contain many tens of subcarriers, without the rigid assumption of the applicability of a single set of weights across the wideband bandwidth. The sub-bands may be statically or dynamically allocated and may, for example, be based upon pilot frequencies within the OFDM signal.

Equation 3, below, shows the format of a weight vector  $V_{\text{weights}}$  for one beam direction, direction  $i$ . A first beam direction is labeled by  $i = 1$ ;  $i = 2$  for a second beam direction and so on. The application of the above-described techniques where more than one direction of arrival is defined is discussed in more detail below with reference to FIGS. 10 and 11.

In equation 3 the superscript  $f$  denotes the frequency of one of the sub-bands, so that  $f_1$  denotes the frequency of the first sub-band and  $f_m$  denotes the frequency of the  $m$ th sub-band. The subscripts 1 to  $n$  label the antenna array elements. Thus, for example,  $XXX$  denotes the pre-FFT weight for the first antenna element at the center frequency of the first sub-band, for the  $i$ th formed beam.

$$V_{\text{weights}} = \begin{bmatrix} w_{i,1}^{f_1} & w_{i,2}^{f_1} & \cdots & w_{i,n-1}^{f_1} & w_{i,n}^{f_1} \\ w_{i,1}^{f_2} & w_{i,2}^{f_2} & \cdots & w_{i,n-1}^{f_2} & w_{i,n}^{f_2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{i,1}^{f_{m-1}} & w_{i,2}^{f_{m-1}} & \cdots & w_{i,n-1}^{f_{m-1}} & w_{i,n}^{f_{m-1}} \\ w_{i,1}^{f_m} & w_{i,2}^{f_m} & \cdots & w_{i,n-1}^{f_m} & w_{i,n}^{f_m} \end{bmatrix}$$

(Equation 3)

5 Referring to FIG. 10, this shows the architecture of an OFDM receiver 1000 with pre-FFT digital beam forming (DBF) and post-FFT diversity, helpful for understanding the operation of the receiver of FIG. 11. The hybrid architecture of FIG. 10 includes time-domain

10 DoA 1002 and DBF 1004 processing for forming two beams, each in a direction with a high signal-to-interference ratio. As in the arrangement of FIG. 8, an array antenna with n elements is employed so that up to n-1 directions may be defined although, in the arrangement

15 of FIG. 10, only two directions are defined. The DoA process 1002 is based upon a Fourier method and operates in a corresponding manner to that for a narrow band system.

In the arrangement of FIG. 10 the DoA 1002 and DBF

20 1004 processing operates in the pre-FFT domain to generate two sets of weights 1006, 1008, each set multiplying 1010, 1012 signals from each of the antenna elements so that after summation 1014, 1016 of the signals two separate beam directions are defined. The

25 signals 1018, 1020 from each of these beam directions



are then FFT processed 1022, 1024 in a conventional manner to provide two pluralities of sub-carrier signals 1026, 1028, one set of subcarriers from each beam direction. The subcarriers are weighted 1030, 1032 according to an angular diversity process 1034 and the diversity combined by summing 1036 a version of each sub-carrier from each beam direction. The subcarriers are then processed 1038 in a conventional manner. It will be understood that the sub-carrier weightings 1030, 1032 will, in general, be complex, that is comprise both amplitude and phase values.

Referring now to FIG. 11, this shows a receiver architecture 1100 broadly similar to that of FIG. 8 but incorporating angular diversity along the lines illustrated in the receiver of FIG. 10. The portion of the receiver 1100 above dashed line 1102 broadly corresponds to the receiver 800 of FIG. 8. Thus like elements have been given like reference numerals and, in particular, the DoA and DFB processing blocks correspond to the beam steering process 832 of FIG. 8. However by contrast with FIG. 8, and similarly to FIG. 10, these processing blocks calculate two sets of weights vectors 1104, 1106, defining first and second beams. The weights vector 1104 is calculated in a corresponding manner to the FIG. 8 arrangement, to define a first beam but, in addition, a second weights vector 1106 is also determined to define a second beam

direction of arrival. This is schematically illustrated by weights 1108, although a single input into DoA processing 832 is sufficient to determine more than one beam direction so that the conceptually  
5 illustrated signals from array antenna elements 802, as weighted by second weights vector 1106, are noted needed by the DoA and DBF processing. As before, the beam directions are determined to maximize the signal-to-interference ratio and thus the two weights vectors  
10 1104, 1106 preferably each define a beam direction with a high signal-to-interference ratio, for example the directions with the highest and next highest signal-to-interference ratio. It will be appreciated that although the arrangement of FIG. 11 only determines two  
15 different beam directions diversity reception may employ a plurality of such beam directions, up to  $n-1$  directions, where  $n$  is the number of antenna elements.

As previously described the two weights vectors 1104 and 1106 are each used to generate a set of post-  
20 FFT weights, for each subcarrier within each beam direction processed. Thus below dashed line 1102 the receiver provided with corresponding elements 816', 818', 840' to the receiver of FIG. 8 which, for conciseness, will not be described again. A set of  
25 subcarrier signals 1109, 1110 is thus obtained for each beam direction (for simplicity only three subcarrier signals are shown in FIG. 11). These are weighted

using respective multipliers 1112, 1114 by applying  
(complex) weights determined by diversity processing  
unit 1116, which operates in a broadly similar manner  
to diversity processing unit 1034 of FIG. 10. Each  
5 weighted subcarrier from one beam direction is then  
combined with its counterpart from one or more other  
defined beam directions, in summers 1118, before  
further processing in a conventional manner, beginning  
with parallel to serial conversion 1120 to provide a  
10 data output 1122 for decoding. It will be appreciated  
that although, for simplicity, FIGS. 11A and 11B show  
the processing required for two beam directions,  
subcarriers from more than two beam directions may be  
combined for greater diversity gain.

15           The invention has been described with reference to  
a receiver but the skilled person will appreciate that  
once a set (or sets) of weights has been determined in  
the frequency domain, this same set (or sets) of  
weights may be applied when transmitting signals. In  
20 other words the weights may be employed to provide a  
spatial pattern for a transmit antenna which mitigates  
co-channel interference since, so far as concerns the  
radio channel, transmission and reception are  
symmetrical. This is particularly the case where  
25 transmission and reception are at the same frequency,  
for example in a time division duplex (TDD) system.

No doubt many effective alternatives will occur to

the skilled person and the invention is not limited to the described embodiments but encompasses modifications within the spirit and scope of the attached claims.

## C L A I M S

1. A signal processing system for determining weights for an adaptive antenna, the antenna having a plurality of antenna elements each for receiving a signal comprising a plurality of subcarriers, the system comprising:

a plurality of inputs for receiving signals from said plurality of antenna elements;

a time-to-frequency domain transformer for each input for transforming the signal from each input to a plurality of subcarrier signals;

a first weight determiner coupled to said inputs, before the time-to-frequency domain transformer in the signal path, and configured to determine a first set of weights, one for each input; and

a second weight determiner coupled to said first weight determiner and configured to determine, from the determination of said first set of weights, at least one second set of weights comprising a frequency-domain weight for a subcarrier signal derived from each of said inputs.

2. A signal processing system as claimed in claim 1, wherein said second weight determiner is configured to determine a plurality of second sets of weights, one second set of weights for each subcarrier signal.

3. A signal processing system as claimed in

claim 1 or 2, further comprising a channel estimator for each said input to provide at least one channel estimate for the signal from each input to the second weight determiner.

5           4. A signal processing system as claimed in claim 1, 2 or 3, further comprising a combiner to combine, for each of said subcarrier signals, a set of weighted versions of the subcarrier signal derived by applying one of said second sets of weights to a set of  
10 versions of said subcarrier signal, one from each of said inputs.

          5. A signal processing system as claimed in any preceding claim wherein said first set of weights defined at least one antenna beam direction and wherein  
15 each second set of weights defines substantially the same antenna beam direction for one of said subcarriers.

          6. A signal processing system as claimed in claim 5, wherein said first set of weights defines a  
20 plurality of antenna beam directions and wherein each second set of weights defines substantially the same plurality of beam directions for one of said subcarriers.

          7. A signal processing system as claimed in any  
25 preceding claim wherein said first weight determiner implements an algorithm to determine a directional response of said antenna.

8. A signal processing system as claimed in claim 7, further comprising a signal and interference detector for determining a signal-to-interference ratio for each of said received signal inputs, and wherein  
5 said algorithm determines said directional response using said signal-to-interference ratios.

9. A signal processing system as claimed in claim 8, wherein said signal and interference detector comprises at least one cross-correlator to determine a  
10 correlation between a said received signal and a first reference signal and between the received signal and a second reference signal at least partially orthogonal to the first reference signal, to provide said signal and interference output.

15 10. A signal processing system as claimed in claim 9, wherein said first and second reference signals each comprise a set of substantially orthogonal carriers.

11. A signal processing system as claimed in  
20 claim 9 or 10, further comprising a reference signal generator to generate said first and second reference signals for said signal and interference detector.

12. A signal processing system as claimed in any preceding claim further comprising a third weight  
25 determiner coupled to said time-to-frequency domain transformer to receive one or a group of said subcarrier signals transformed from each of said



received signal inputs and configured to determine a third set of weights for said one or said group of subcarrier signals.

13. A signal processing system as claimed in  
5 claim 1, wherein said first weight determiner is configured to determine a plurality of said first sets of weights, one for each of a plurality of sub-bands of said signal comprising a plurality of subcarriers.

14. A signal processing system as claimed in  
10 claim 13, wherein said second weight determiner is configured to determine a plurality of second sets of weights, one for each subcarrier, using said plurality of first sets of weights.

15. A signal processing system as claimed in  
15 claim 14, wherein each said subcarrier is allocated to one of said sub-bands, and wherein said second weight determiner is configured to determine a said second set of weights using the first set of weights for the sub-band to which the subcarrier is allocated.

20 16. A signal processing system as claimed in claim 1 wherein, said first weight determiner is configured to determine a plurality of said first sets of weights defining a corresponding plurality of antenna beam directions.

25 17. A signal processing system as claimed in claim 16, wherein said second weight determiner is configured to determiner a plurality of said second

sets of weights, one for each said beam direction.

18. A signal processing system as claimed in claim 17, further comprising a diversity processor and a combiner coupled to said diversity processor to  
5 combine versions of a said subcarrier signal weighted by a weight from each of said plurality of second sets of weights.

19. A signal processing system as claimed in any preceding claim wherein a said received signal  
10 comprises an OFDM signal and wherein said transformer is configured to fourier transform the received signal.

20. A signal processing system as claimed in claim 1, wherein said first weight determiner is replaced by an antenna signal processor configured to  
15 determine a direction of arrival of a signal received at the antenna, and wherein said second weight determiner is configured to determine the second set of weights using said direction of arrival.

21. A method of determining weights for an  
20 adaptive antenna, the antenna having a plurality of antenna elements each for receiving a signal comprising a plurality of subcarriers, the method comprising:

receiving a plurality of signals from said  
plurality of antenna elements;

25 transforming each of said plurality of received signals into a plurality of subcarrier signals;

determining a first set of weights, one for each

received signal; and

determining, using the determination of said first set of weights, at least one second set of weights comprising a frequency-domain weight for a subcarrier signal derived from each of said received signal inputs signals.

22. A method as claimed in claim 21 comprising determining a plurality of second sets of weights, one second set of weights for each subcarrier signal.

10 23. A method as claimed in claim 21 or 22, further comprising:

estimating a channel response for each of said received signals; and

15 using said channel responses to determine said second sets of weights.

24. A method as claimed in claim 21, 22 or 23, further comprising:

20 combining, for each of said subcarrier signals, a set of weighted versions of a said subcarrier signal derived by applying one of said second sets of weights to a set of versions of said subcarrier signal, one from each of said received signals.

25 25. A method as claimed in any one of claims 21 to 24, wherein said first set of weights defines at least one antenna beam direction and wherein each second set of weights defines substantially the same antenna beam direction for one of said subcarriers.

26. A method as claimed in any one of claims 21 to 24, wherein said first set of weights defines a plurality of antenna beam directions and wherein each second set of weights defines substantially the same plurality of beam directions for one of said subcarriers.

27. A method as claimed in any one of claims 21 to 26, wherein said determining of a first set of weights includes implementing an algorithm to determine a directional response of said antenna.

28. A method as claimed in claim 27, further comprising:

determining a signal-to-interference ratio for each of said received signals; and wherein said algorithm determines said directional response using said signal-to-interference ratios.

29. A method as claimed in claim 28, wherein each said signal-to-interference ratio is determined by correlating a portion of a signal received by an antenna element with a first reference signal and with a second reference signal at least partially orthogonal to the first.

30. A method as claimed in claim 29, wherein said first reference signal comprises a set of substantially orthogonal carriers.

31. A method as claimed in claim 30, wherein the carriers of said first reference signal are modulated

by a known data sequence.

32. A method as claimed in any one of claims 21 to 31, further comprising:

5 determining a third set of weights for one or a group of said subcarrier signals.

33. A method as claimed in claim 21, comprising determining a plurality of said first sets of weights, one for each of a plurality of sub-bands of said signal comprising a plurality of subcarriers.

10 34. A method as claimed in claim 33, comprising determining a plurality of second sets of weights, one for each subcarrier, using said plurality of first sets of weights.

15 35. A method as claimed in claim 34, wherein each said subcarrier is allocated to one of said sub-bands, and further comprising determining said second set of weights using the first set of weights for the sub-band to which the subcarrier is allocated.

20 36. A method as claimed in claim 21, comprising determining a plurality of said first sets of weights defining a corresponding plurality of antenna beam directions.

25 37. A method as claimed in claim 36, comprising determining a plurality of said first sets of weights, one for each said beam direction.

38. A method as claimed in claim 37, further comprising combining versions for a said subcarrier

signal weighted by a weight from each of said plurality of second sets of weights..

39. A method as claimed in any one of claims 21 to 38, wherein a said received signal comprises an OFDM signal and wherein said transforming implements a fourier transform.

40. A method of adaptive beamforming for an OFDM antenna comprising a plurality of antenna elements, the method comprising:

10       applying a first beamforming algorithm in the time domain to determine at least one antenna beam direction; and

15       calculating a set of weights for application in the frequency domain to versions of at least one subcarrier, each version of the subcarrier being received by a corresponding one of the antenna elements;

      said set of weights being calculated using said at least one antenna beam direction.

20       41. A method of calculating weights for an array antenna for receiving an orthogonal frequency division multiplexed (OFDM) signal comprising a plurality of subcarriers, the method comprising:

25       determining, in a time domain, a direction of arrival of the OFDM signal at the array antenna;

      calculating at least one set of weights for application to the subcarriers of the OFDM signal in a

frequency domain using said direction of arrival.

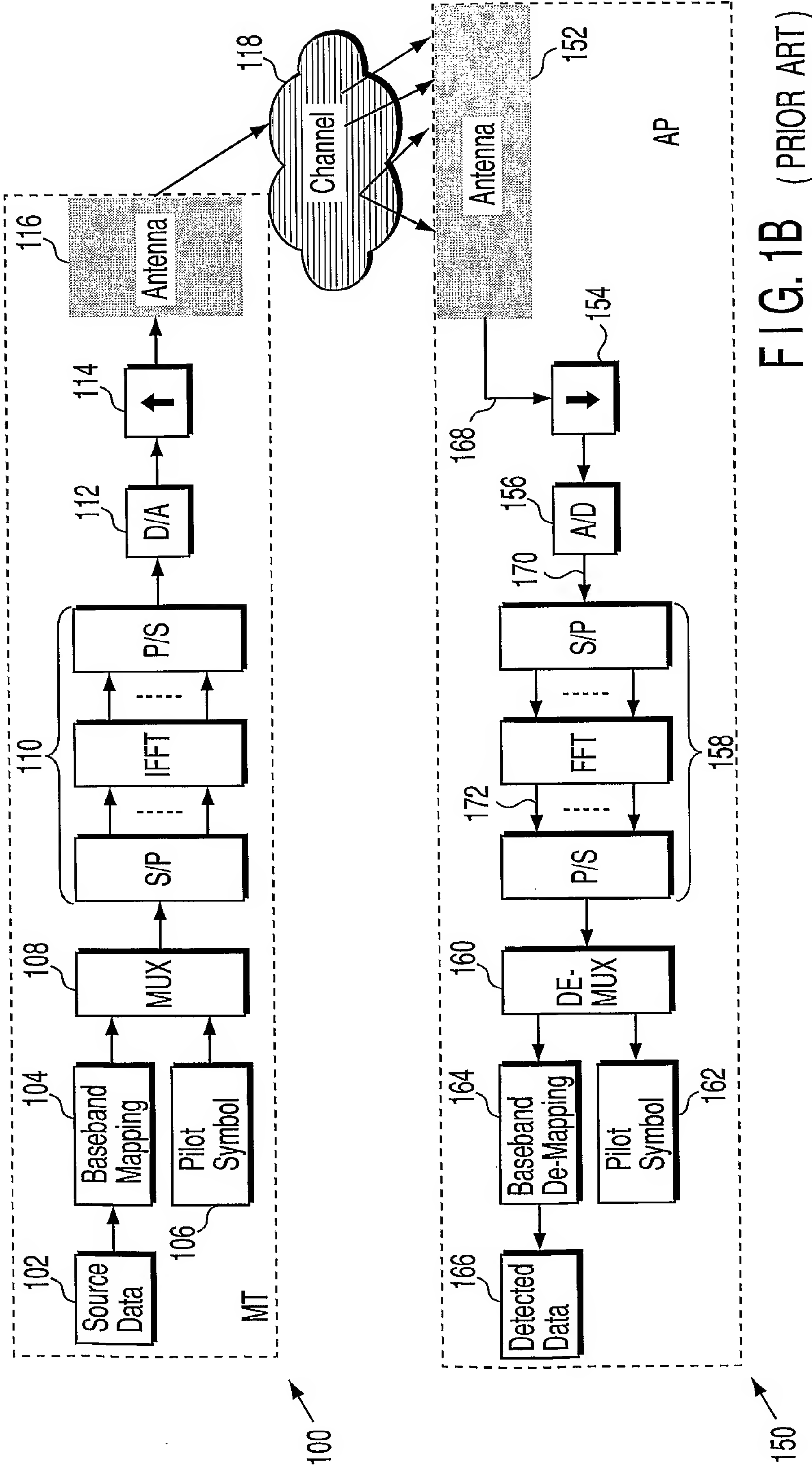
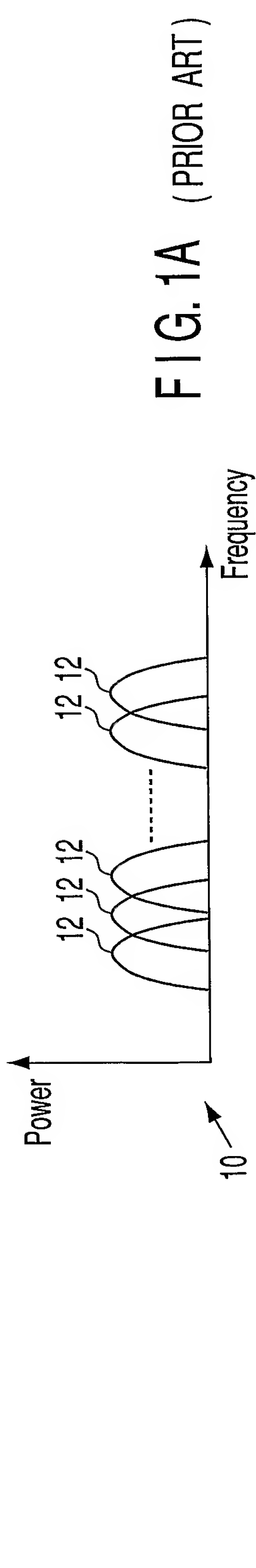
42. A method as claimed in claim 41;  
calculating a plurality of said sets of weights,  
one for each subcarrier, using said direction of  
5 arrival.

43. A processing system for an adaptive antenna  
configured to implement the method of claim 41 or 42.

44. Processor control code to, when running,  
implement the signal processing system of any one of  
10 claims 1 to 20 or the method of any one of claims 21  
to 42.

45. A carrier carrying the processor control code  
of claim 44.





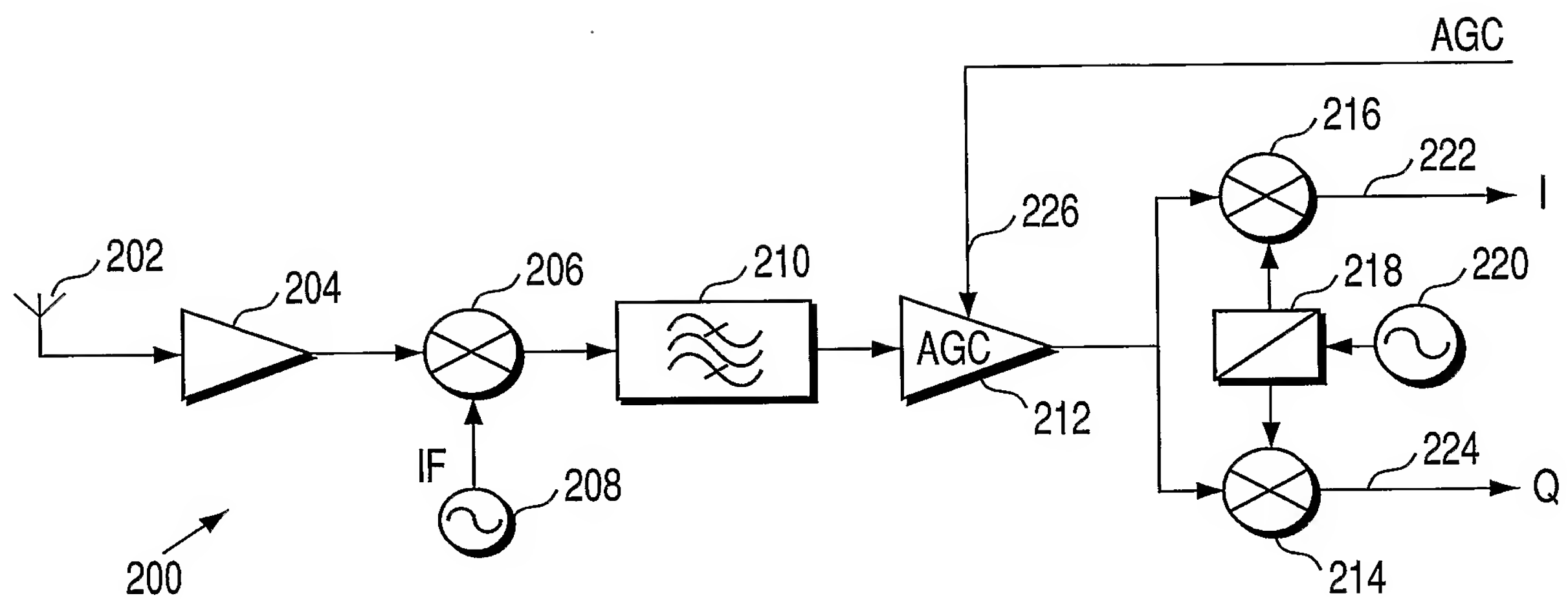


FIG. 2A (PRIOR ART)

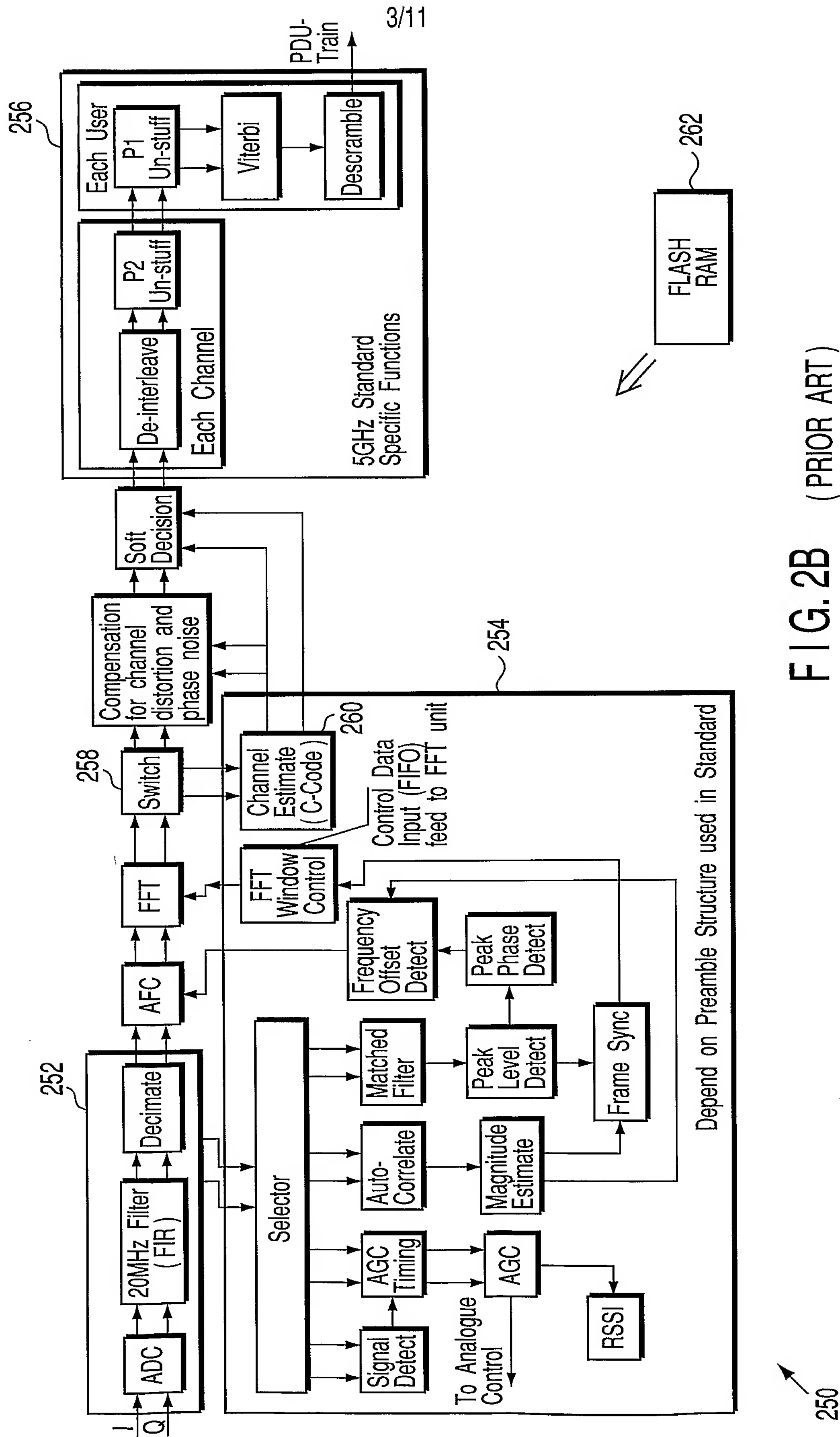


FIG. 2B (PRIOR ART)

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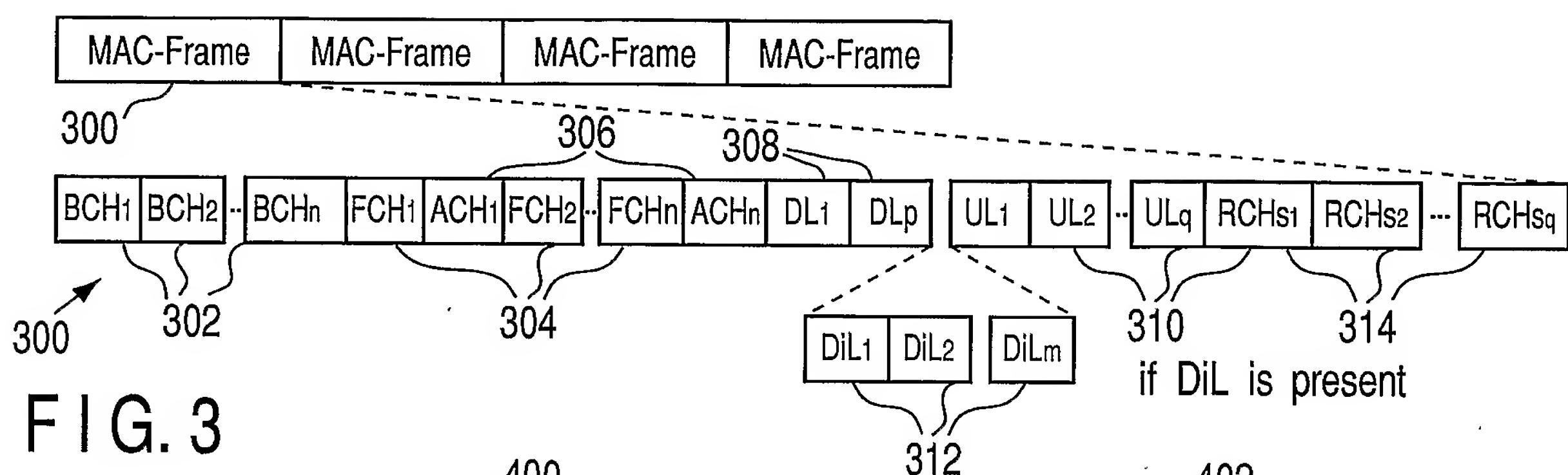


FIG. 3

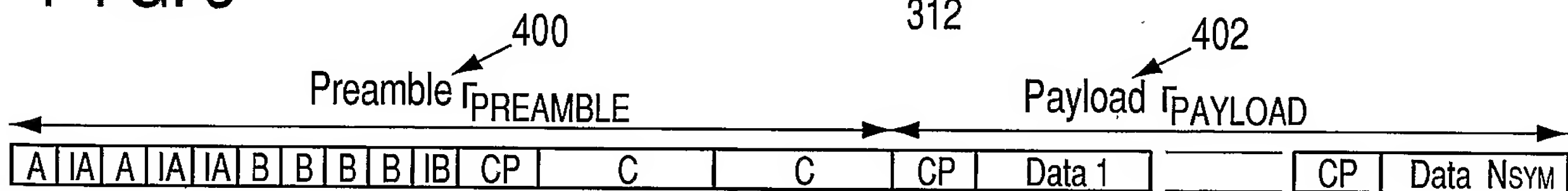


FIG. 4 A

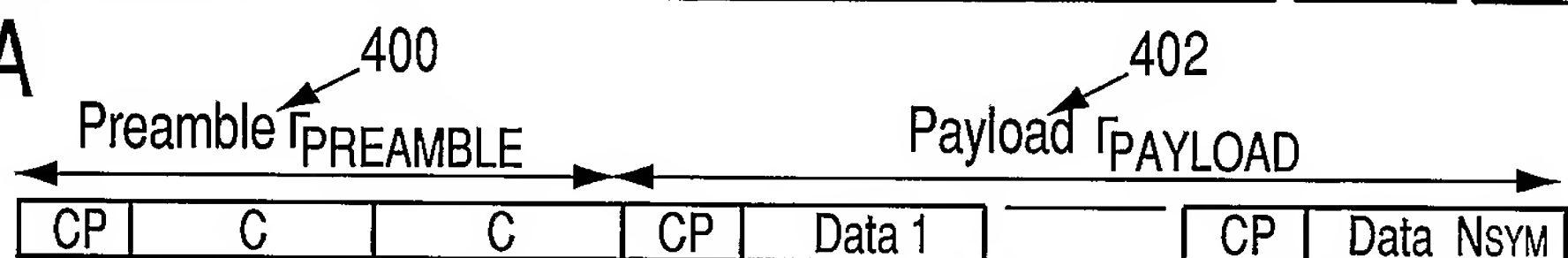


FIG. 4 B

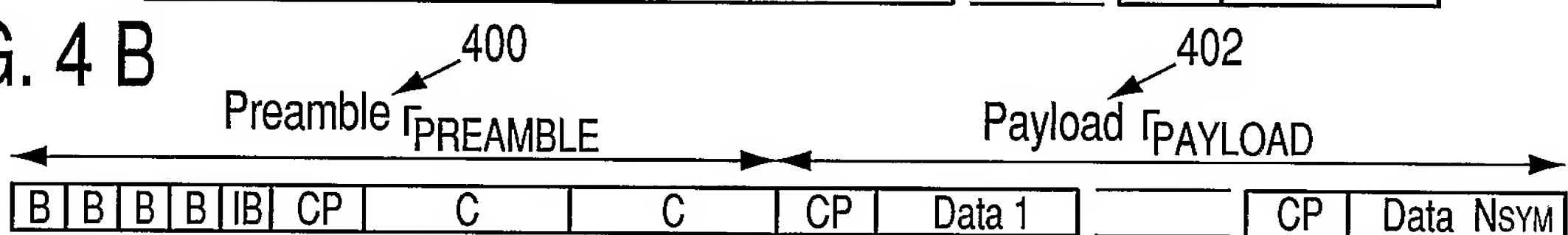


FIG. 4 C

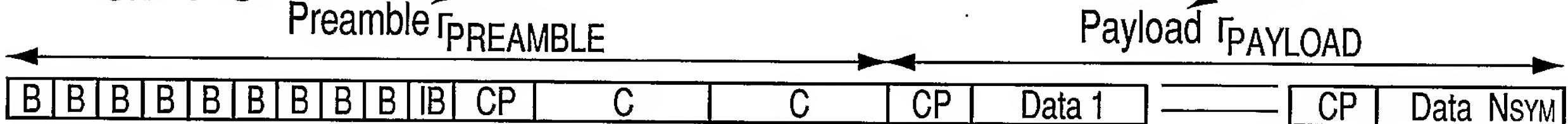


FIG. 4 D

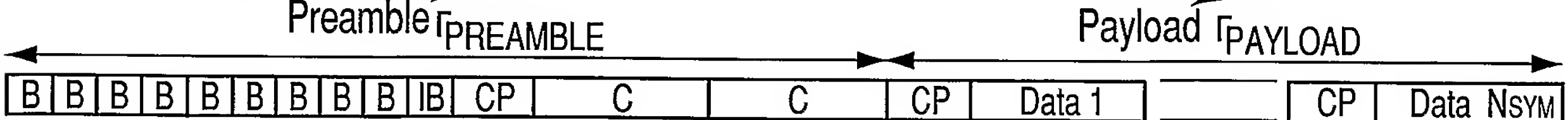


FIG. 4 E

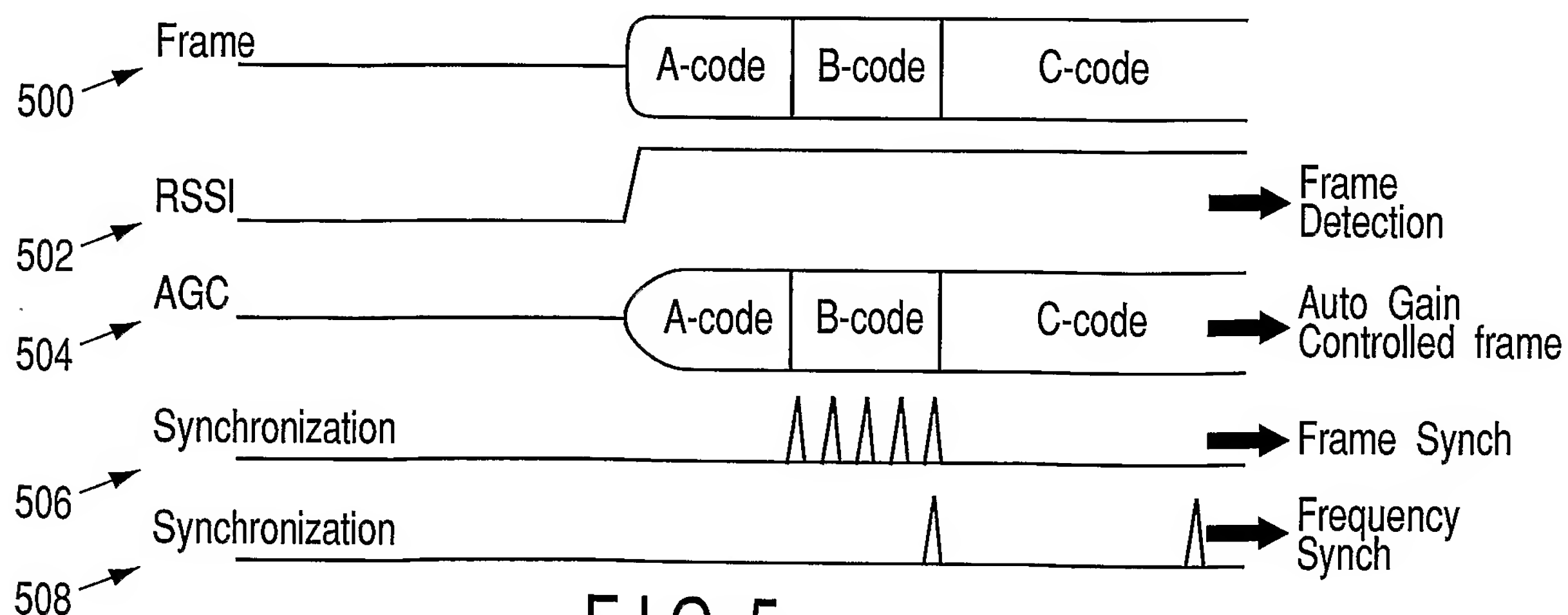


FIG. 5

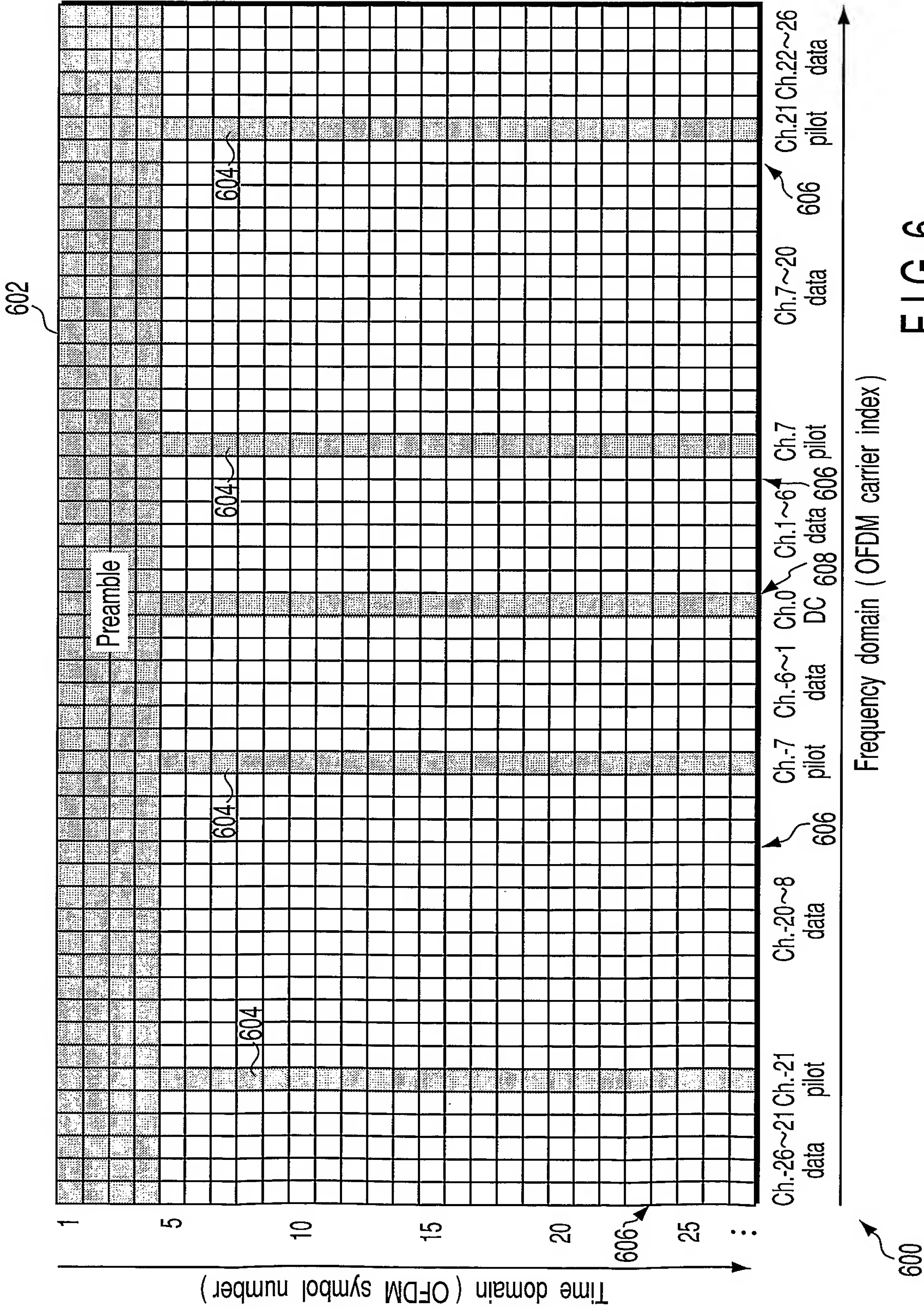


FIG. 6

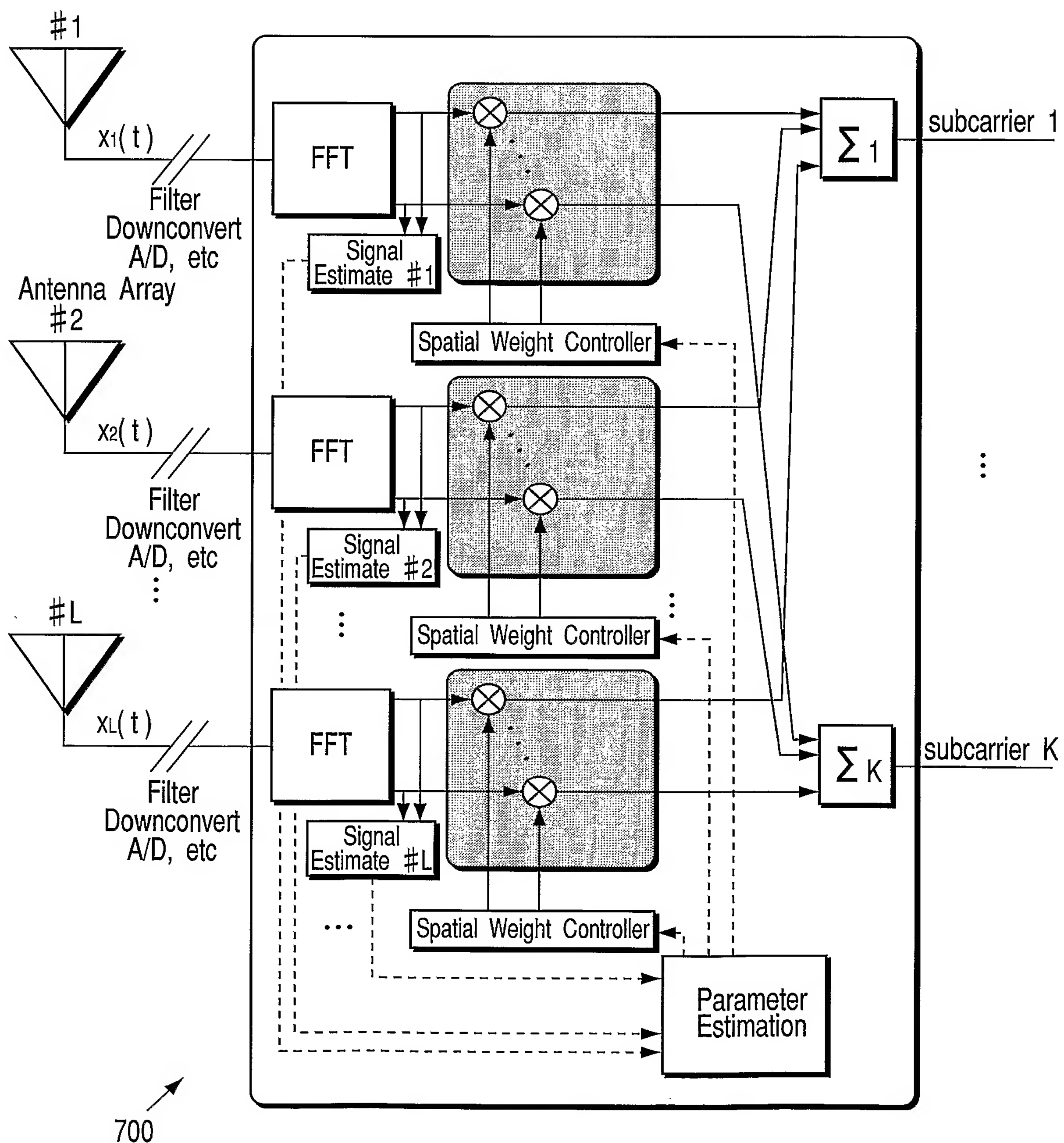
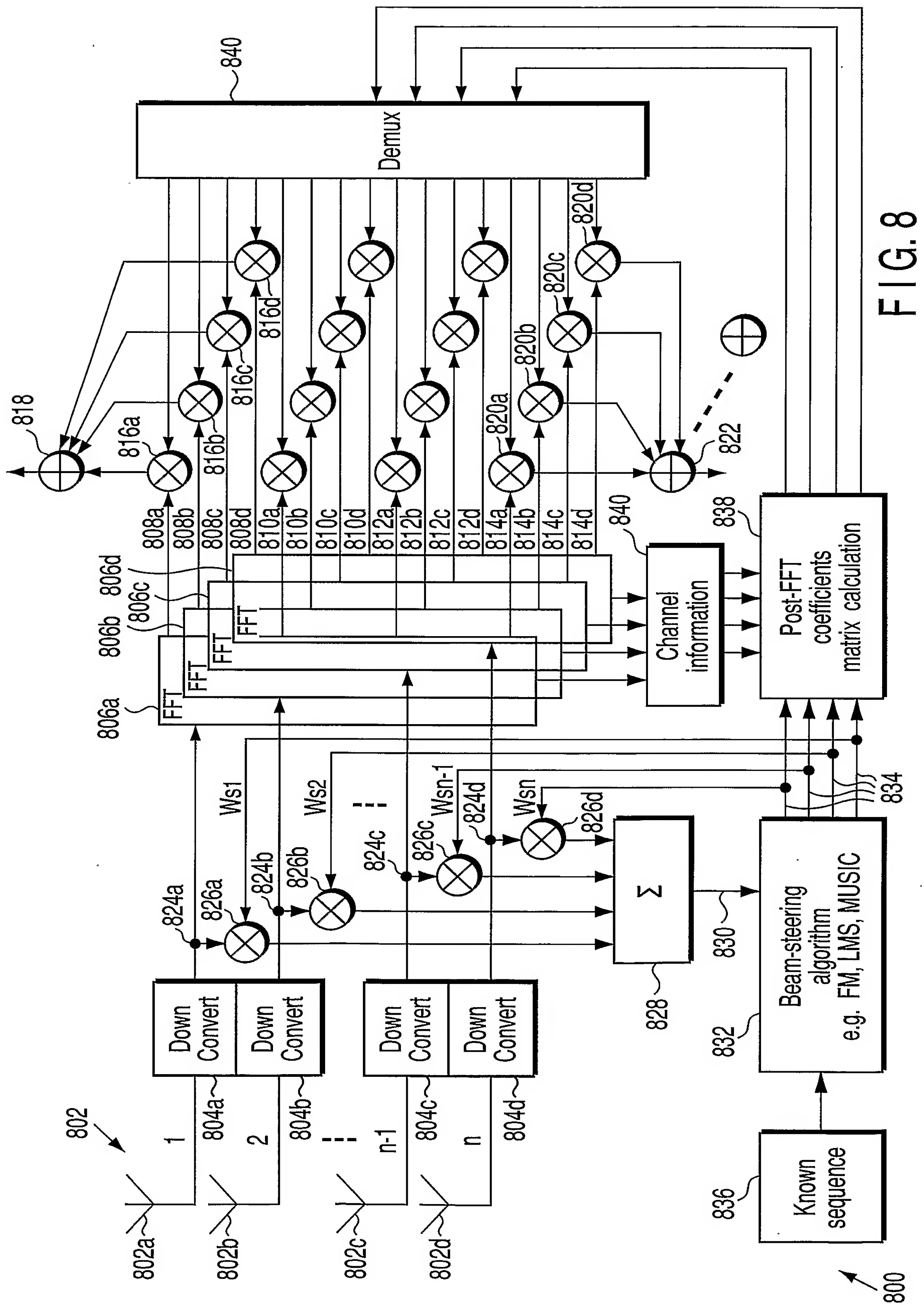


FIG. 7

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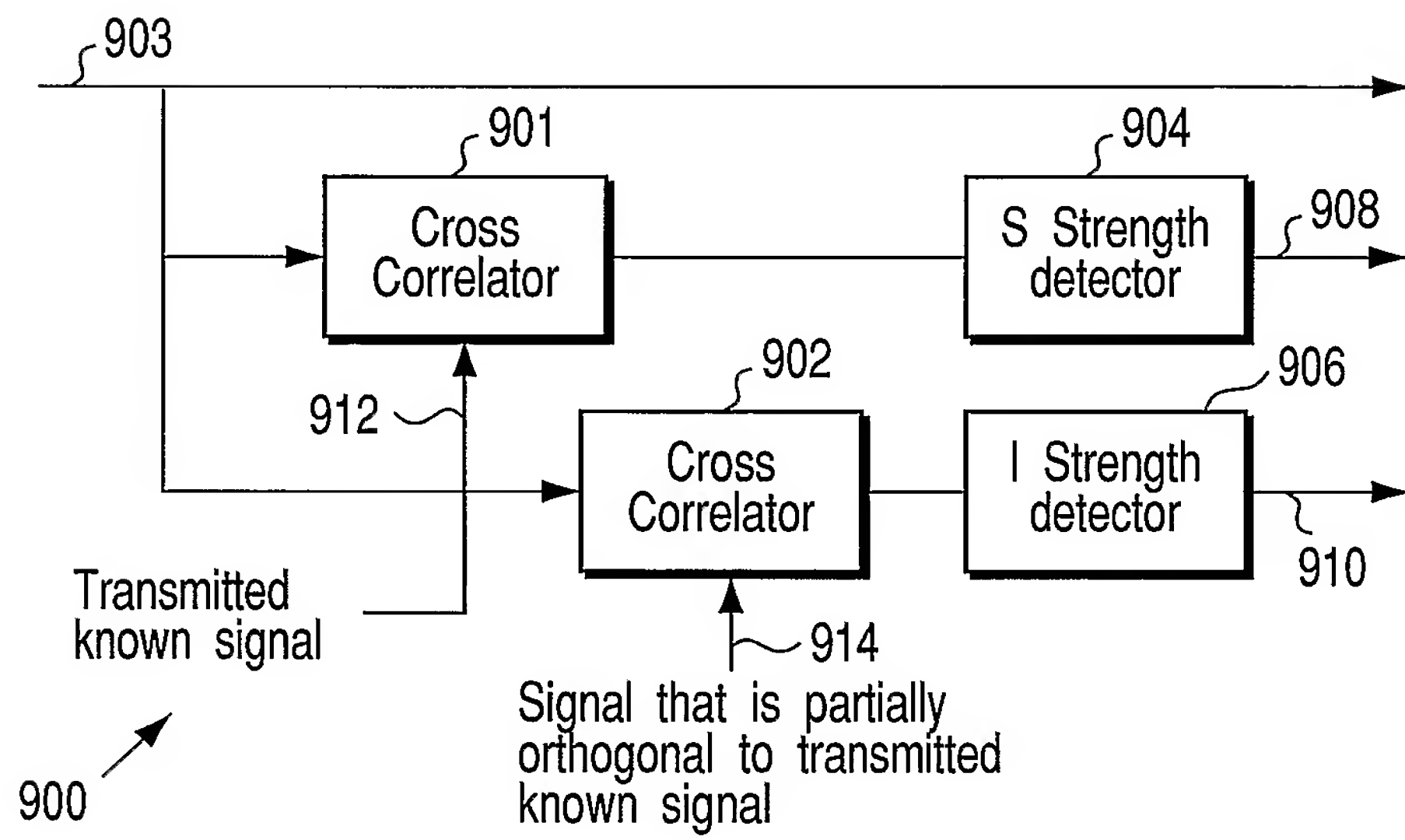


FIG. 9A

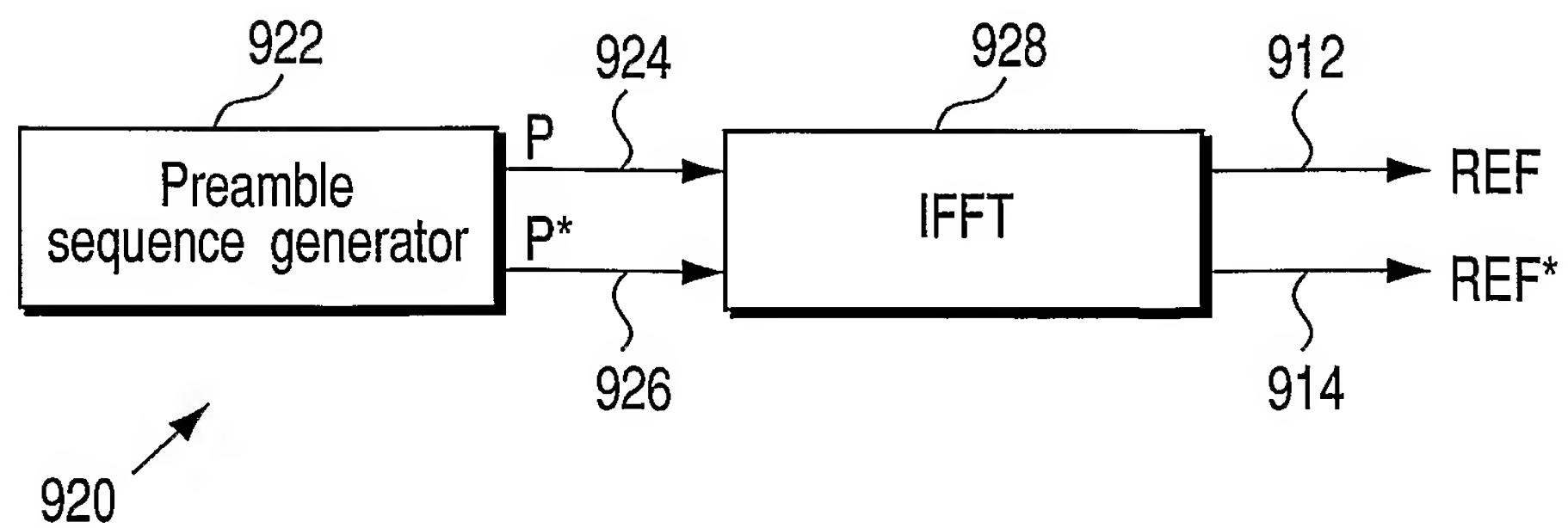


FIG. 9B

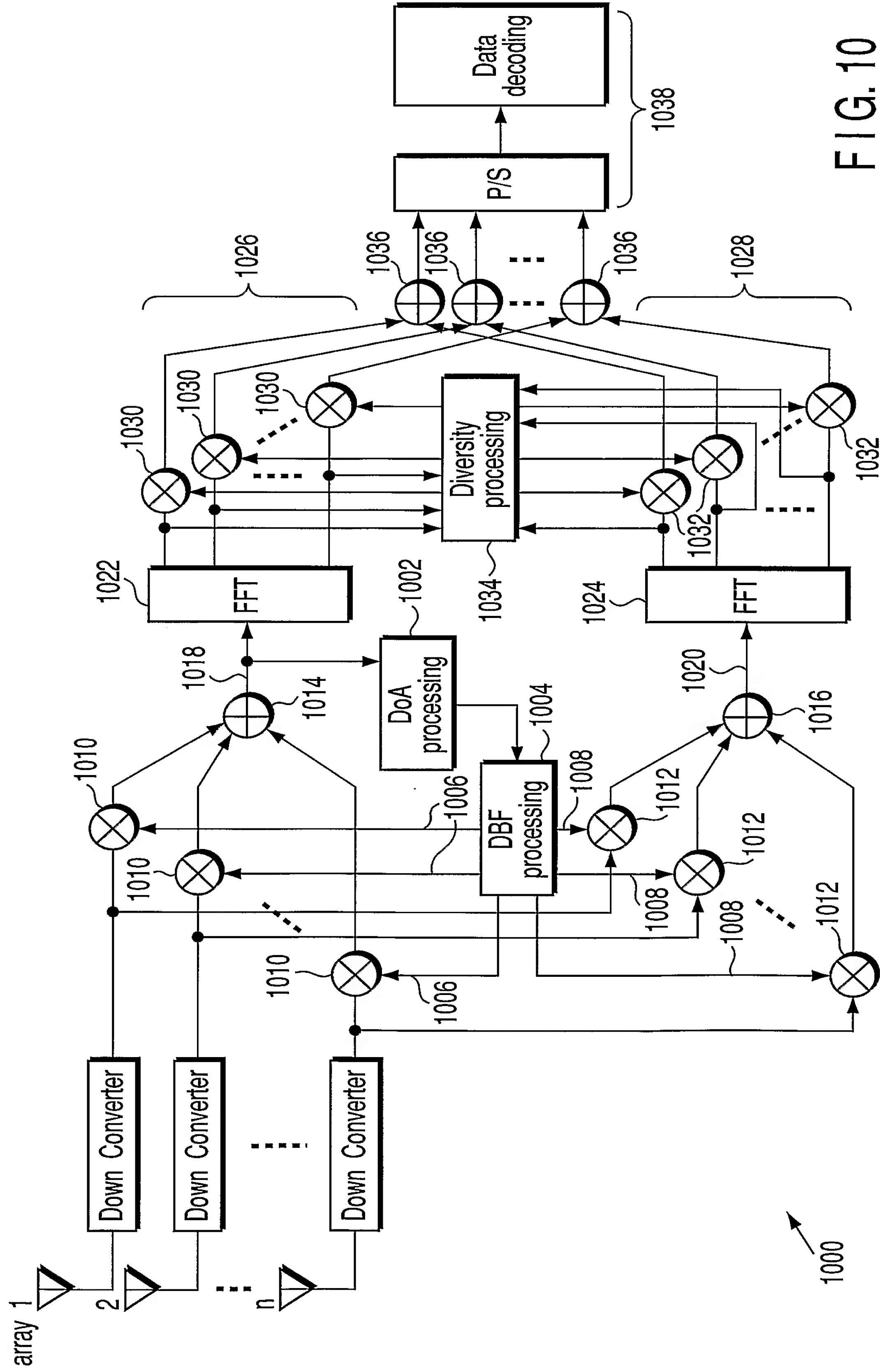


FIG. 10

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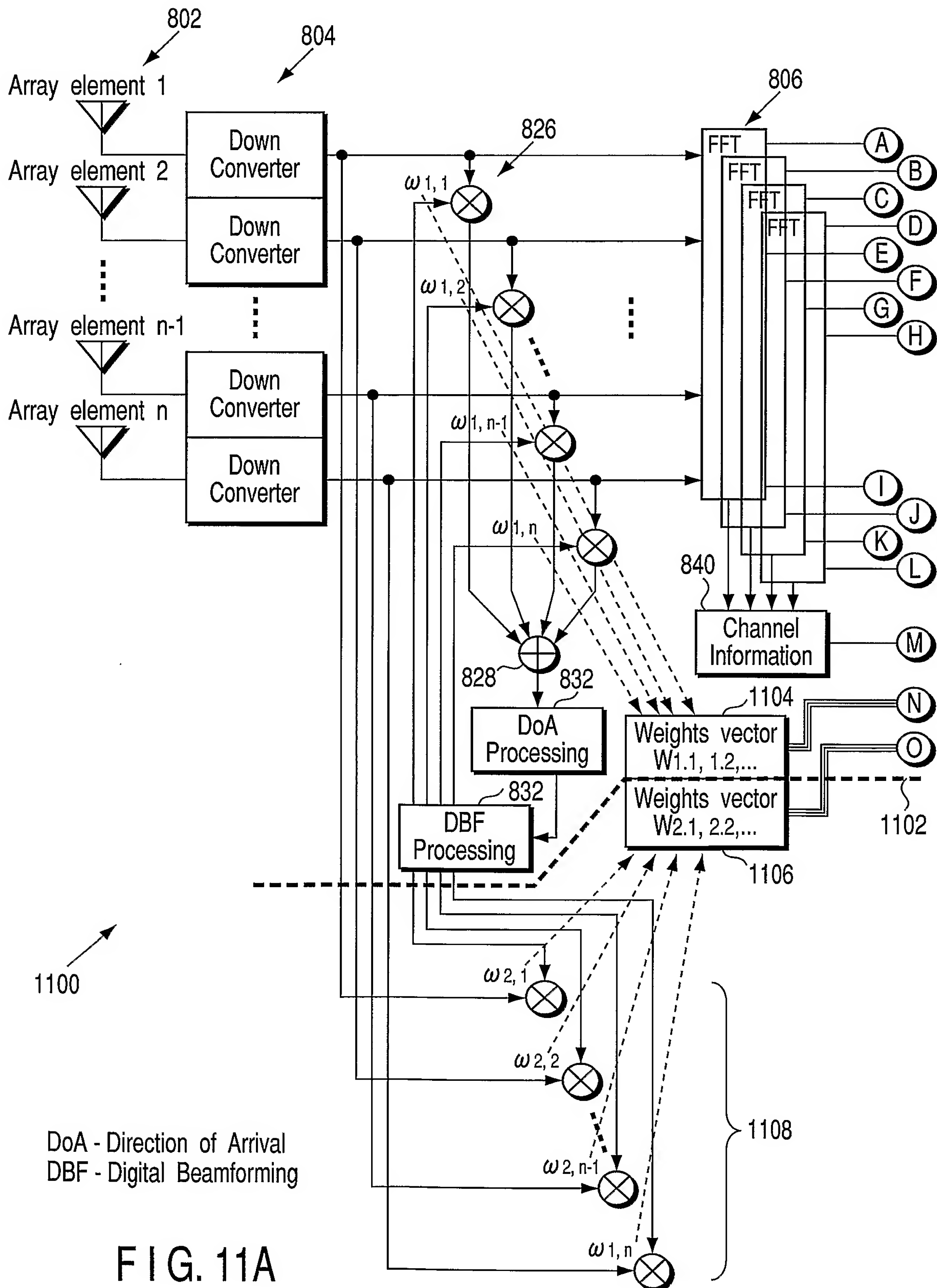


FIG. 11A

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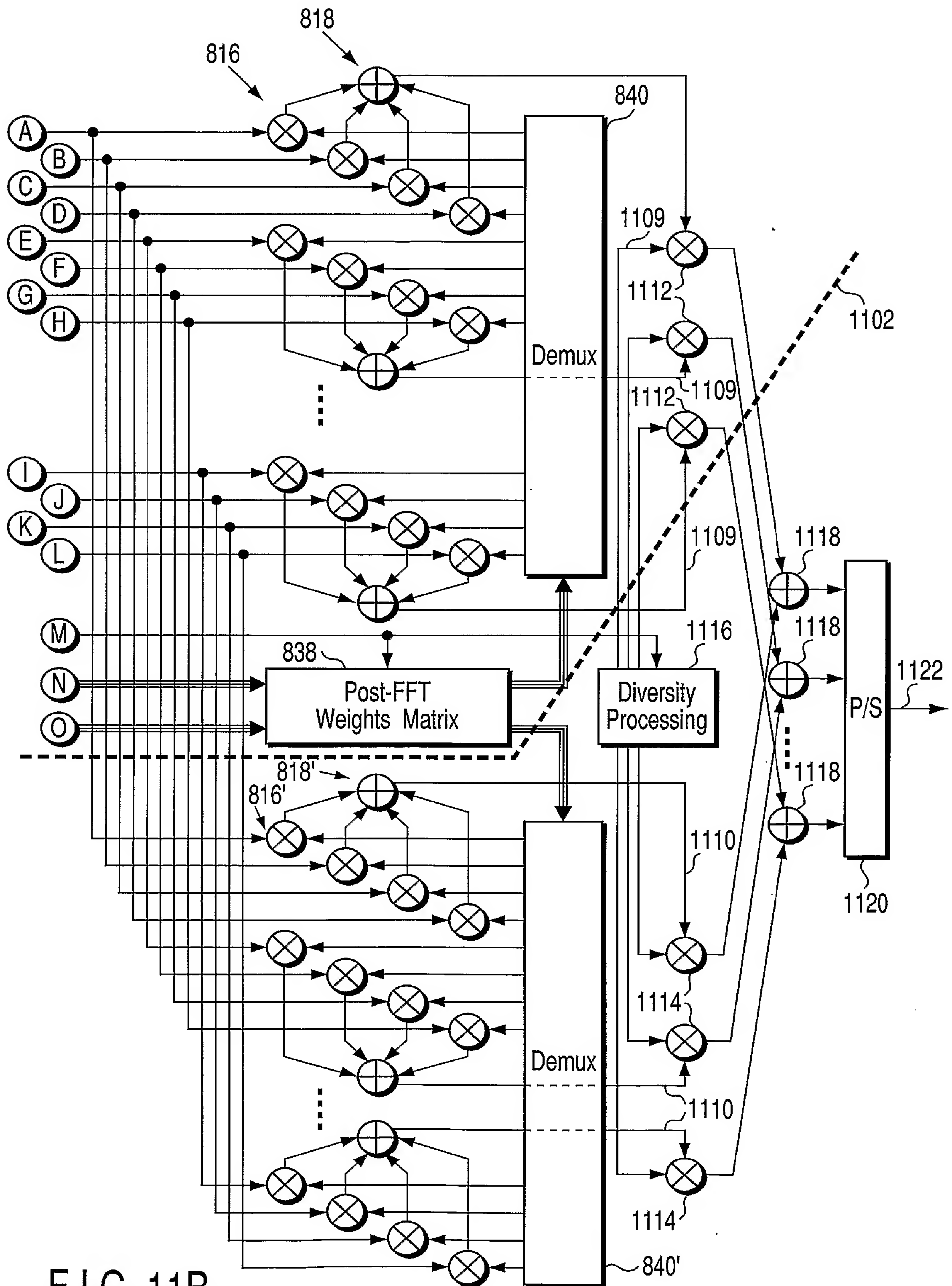


FIG. 11B

## INTERNATIONAL SEARCH REPORT

International Application No

PCT/JP 03/02935

A. CLASSIFICATION OF SUBJECT MATTER  
 IPC 7 H04L27/26 H04B7/08

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04L H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	OKADA M ET AL: "A joint frequency and space diversity scheme for OFDM" VEHICULAR TECHNOLOGY CONFERENCE, 1999. VTC 1999 - FALL. IEEE VTS 50TH AMSTERDAM, NETHERLANDS 19-22 SEPT. 1999, PISCATAWAY, NJ, USA, IEEE, US, 19 September 1999 (1999-09-19), pages 2939-2943, XP010353353 ISBN: 0-7803-5435-4 the whole document	1,21,40, 41
A	EP 0 844 765 A (TOYODA CHUO KENKYUSHO KK) 27 May 1998 (1998-05-27) column 15, line 24 -column 18, line 52; figures 4,8	1,21,40, 41
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Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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- \*O\* document referring to an oral disclosure, use, exhibition or other means
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- \*T\* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search

11 July 2003

Date of mailing of the international search report

24/07/2003

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Burghardt, G

## INTERNATIONAL SEARCH REPORT

International Application No  
PCT/JP 03/02935

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>FUJIMOTO M ET AL: "A NOVEL ADAPTIVE ARRAY UTILIZING FREQUENCY CHARACTERISTICS OF MULTI-CARRIER SIGNALS" IEICE TRANSACTIONS ON COMMUNICATIONS, INSTITUTE OF ELECTRONICS INFORMATION AND COMM. ENG. TOKYO, JP, vol. E83-B, no. 2, February 2000 (2000-02), pages 371-379, XP001063877 ISSN: 0916-8516 cited in the application abstract page 372, left-hand column, line 6 -page 374, right-hand column, line 13; figure 2 -----</p>	1,21,40, 41

## INTERNATIONAL SEARCH REPORT

### Information on patent family members

**International Application No**

PCT/JP 03/02935

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			JP	10210099 A	07-08-1998
			CA	2221904 A1	22-05-1998
			DE	69722566 D1	10-07-2003
			EP	0844765 A2	27-05-1998
			US	6115426 A	05-09-2000
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